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ANALYSIS OF THE IMPLEMENTATION OF A PHOTOVOLTAIC PLANT IN CATALONIA

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1. INTRODUCTION

Energy is a basic need for humanity. Simply, look back, and see that even for the primitive man was essential to develop any kind of activity.

Currently, energy consumption is based on waste from fossil fuels like oil, coal and gas. These sources are not inexhaustible and these can cause environmental degradation.

The increasing energy demand generally in developed countries, where we are included, is due to their lifestyle. Thus, it is anticipated that the primary energy demand in the world in mid-century XXI will double or triple the current demand, owing to the increasing industrialization, economic development and the population growth. With this consumption of fossil reserves created by nature during centuries will be extinct. It is estimated that reserves of oil, gas and coal will be exhausted in 21, 65 and 155 years respectively, at current rates.

Thus, the only alternatives that remain are nuclear fusion energy, which still has much to develop, and renewable energies. In front of conventional sources, the renewable energies are clean and inexhaustible resources provided by the nature with practically no impact on the environment.

Within the renewable energies, there is hydropower energy, which is almost saturated in Spain, requiring large extensions of land; the wind energy which is the one which has had the greatest boom in recent years in Spain; without underestimating the biomass, which nowadays represents almost the 4% of the energy consumption in the European Union, and probably will be the future fuel for vehicles, along with solar thermal and photovoltaic, which are those with higher expectation for the future.

In this project we will focus on solar photovoltaic energy. Each year, the sun sheds on the surface of the Earth, four thousand times the energy we use and will continue for several billion of years, World electricity demand is about 17 300 TWh. The average production of a photovoltaic plant in central Europe is 120 kWh/(m2·year), so it would be enough just an area of over 144 000 km2, equivalent to 1,5% of Europe to cover the worldwide demand. It is clear that the sun gives us more energy than we can consume, due to the efficiency used to exploit it.

Based on current market conditions for renewable energy, the social and cultural benefits that suppose to humanity and the good business opportunity, in this project it will be analyzed a project of a photovoltaic plant located in the TM in Abrera, in Catalonia, Spain.

The aim of this project is the technical description of a photovoltaic system, analyzing each of the elements, the presentation of different types of existing plants and the regulation existing in Spain, and presenting a proposal of such a plant basing on the theoretical considerations, next modeling and proper calculations. Anyway, further evaluation of the current energetic, environmental and economic situation in a real photovoltaic plant ought to be conducted and compared. In this project the suggested method is based on real data from the existing photovoltaic power plant.

With all radiation and billing data collected from the real plant, there will be developed energetic, environmental and economic balances of the situation. By this analysis, it will be obtained the energy efficiencies of all the elements and it will be performed the appropriated balance between theoretical and real values. In this way, it will be possible to visualize how the equipment works and the contribution exercised by each one of the elements within the plant.

Aside of the technical and economical aspects of the proposed solution, the environmental problems are also taken into consideration according to the EU standard and needs.

2. SOLAR PHOTOVOLTAIC ENERGY

The sun's energy is vital for life on Earth, since the solar radiation determines the Earth's surface temperature. The Earth receives about 1367 W/m^2 before entering the atmosphere, 4500 times the energy consumed nowadays. Part of this radiation is reflected by the atmosphere, while the rest is absorbed. The energy reaching the Earth every minute is higher than the energy that consumes the humanity in a year, it is only used a small part, but enough, of the direct and diffused radiation due to factors such as cloud cover, reflection and dispersion.

The solar flux varies with latitude, solar radiation increases at the rate of this, latitude, depending on the angle of incidence of the sunlight, weather and time of the day and season.

Solar photovoltaic energy is the direct conversion of sunlight into electricity, using electronic devices composed of modules called solar cells, which are based on silicon chemically treated silicon. It is used both crystalline and polycrystalline or even amorphous cells for electronic devices such as calculators.

The conversion of solar energy into electrical energy takes advantage of a physical phenomenon known as the photovoltaic effect that occurs when light strikes the cell surface and release atoms and electrons of the semiconductor material. These atoms and electrons are excited by the light, moving through silicon generating a flow of electrons inside these materials, thus a potential difference that can be exploited. Certain chemical elements are added to the composition of silicon which can set a path for electrons to follow, generating then direct current.

The solar irradiation reaches the photovoltaic modules that produce electricity by the photovoltaic effect in form of direct current (DC). This energy can be stored in batteries to be used outside of the daylight hours, or can be injected into the electrical grid previously transformed into alternating current (AC), using an electronic device called inverter.

In order to promote renewable energy and thereby to help to reduce CO_2 emissions, renewable energies and particularly the solar photovoltaic power is subject to grants in many countries of the world to improve their viability and thereby to reduce the return periods of investments.

Spain is currently (2010-11), one of the first countries with the most photovoltaic power in the world, according to the International Energy Program (IEP), and inside the Photovoltaic Power Systems Programme (PVPS), with cumulated installed power of 3 523 MW. In the first year after the regulation imposed by the government where it said that the solar photovoltaic energy generation would be subsidized, there was great growth in deployment of this technology, and in 2008 the installed photovoltaic power in Spain ranged around 2 500 MW. This decrease in growth between 2008 and nowadays, is due to the notice to change the regulation to reduce the bonus of the generation that finally took place in September 2008.

Germany is currently the second-largest manufacturer of photovoltaic solar panels after Japan, with about 5 million square meters of solar panels, which represents only the 0.03% of its total energy production. The sale of photovoltaic panels in the world has grown at an annual rate of 20% in the nineties. In the EU the average annual growth is about the 30%.

The current growth of solar photovoltaic is limited by the lack of raw materials on the market (solar grade silicon) to be taken over the current sources, but from the second half of 2008 the price of solar grade silicon has begun to decrease with the increasing supply due to the entrance of new producers. Proof of this are the various plans that have been established for new producers of this material worldwide, including two projects in Spain with the collaboration of key market players.

The injection of photovoltaic solar energy to the electrical grid was regulated by the Spanish Government through Decree 661/2007, that remunerated with 0,44 € per each kWh injected into the grid. From September 30, 2008, this activity is regulated by Decree 1578/2008 which establish a photovoltaic remuneration variable bonus based on the location of the facility (on the ground: 0,32 €/ kWh or on the roof: 0,34 €/kWh) and it is also subject to an annual maximum quarterly installed power from 2009 to adapt from quarter to quarter depending on the market performance . Keep in mind that this scheme will only be subject to all facilities with final registration after September 2008.

Currently access to the electrical grid in Spain requires a large number of government permits and authorization of the electricity distributor company in the area. This company has the obligation to give connection to the electrical grid, but in practice the bureaucracy and the reluctance of these companies are slowing the momentum of renewable energy. The electrical companies are looking for technical reasons such as network congestion to control their interest in other energy sources and with the intention to block the initiative of small producers of solar photovoltaic energy.

This situation causes a serious contradiction between the objectives of the European Union to promote clean energy and the reality of a limited liberalization of the energy sector in Spain which prevents the free takeoff and competitiveness of renewable energy.

2.1 ELEMENTS OF A PHOTOVOLTAIC PLANT

As we have seen before, a photovoltaic plant consists of different elements to enable the conversion of solar energy into electricity. It is important to notice, that a photovoltaic plant not always consists of these elements, it may dispense with one or more of these, taking into account the type and size of the fed charges, as well as the nature of energy sources in the installation site.

2.1.1 Collection system

This system consists of a set of photoelectric cells, also called photocells or solar cells. These are electronic devices made of silicon, the second most abundant substance in the Earth, which size ranges between 1 and 10 cm of diameter, and that can transform light energy (photons) into electrical energy (electrons) by the photovoltaic effect. It is important to notice, that it accepts both direct and diffuse radiation and can generate electricity even on cloudy days.

These cells are manufactured of a material which benefits from the photoelectric effect: they absorb photons of the sunlight and emit electrons. When the sunlight strikes the surface of the photovoltaic cell, electrons are released from an atom. Electrons, excited by the light, move through the silicon (Fig. 2.1.1.1). Certain chemical elements added to the composition of silicon can set the path to follow the electrons. When these free electrons are captured, the result is an electric direct current that can be used as electricity from a power between 1 and 2 W.

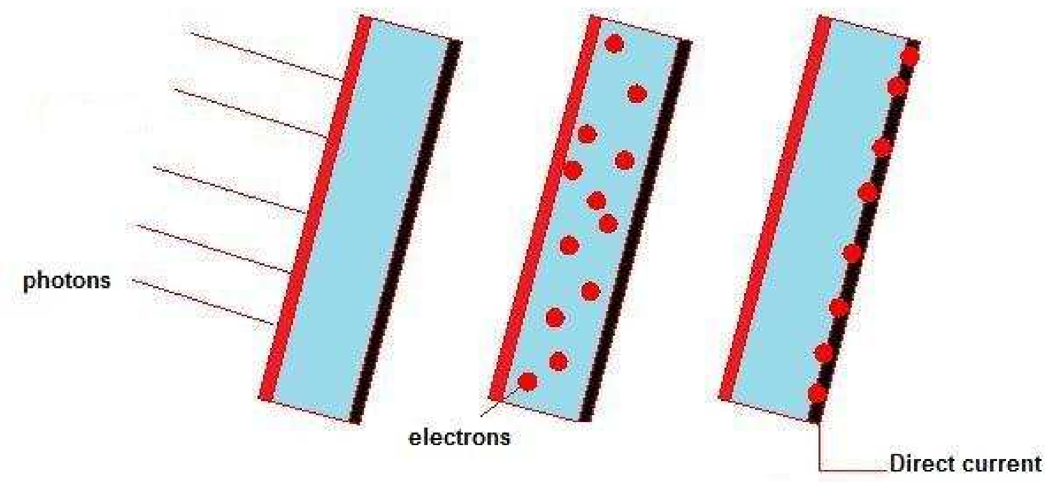


Figure 2.1.1.1-. Photovoltaic effect

The photovoltaic panels according to their composition, are divided into:

- Crystalline
    - *Monocrystalline:* made up of sections of a single silicon crystal. When cooling, the molten silicon solidifies into a single large crystal. Afterwards, the glass is cut into thin layers that give place to cells. The overall aspect is uniform blue. As for features, it has a good performance, between 14 and 16%, and a good area uptake ratio (W_p/m^2), about 150 W_p/m^2 , which saves space if necessary. In addition, it exists a large number of producers even though the cost continues being high.
    - *Polycrystalline:* These are formed by crystallized small particles. During the cooling of the molten silicon, it solidifies creating many crystals. Their appearance is blue too, but it is not uniform, since we can distinguish several different colours created by the glass. As for their characteristics, they have a better performance than the monocrystalline within a module, due to the fact they are square cells, unlike the monocrystalline cells that have rounded edges. Its conversion efficiency is still slightly lower, although still good, and the cost of production is cheaper. The problem with the low performance is shown in low light conditions.

- Amorphous: These cells are produced when the silicon has not yet crystallized during processing, and it produces a gas that is projected onto a glass slide. Its appearance is dark gray and they were the first to be manufactured. These can be seen in calculators, watches, etc. They are able to operate with low diffuse light, even on cloudy days. The cost is much smaller and it can accommodate both flexible and rigid media. Against this, the performance, in full sunlight conditions, is between 5 and 7%, and it decreases, with the pass of time, around 7%.

So, as we have seen, the effectiveness is greater the larger are the crystals, but also its weight, thickness and cost. The first performance can reach the 20% while the last ones can not reach even 10%.However its cost and weigh is much lower.

The average conversion efficiency of photovoltaic cells available in the market nowadays (produced from monocrystalline silicon) is about 11-12%, but depending on the technology used varies from 6% for amorphous silicon cells to 14-19% of monocrystalline silicon cells. There are also multi-layered cells, typically gallium arsenide, which achieve efficiencies of 30%. In laboratories, it has been exceeded 42 % with new experimental photovoltaic panels.

The average lifetime at maximum efficiency is around 25 years, a period from which the output power decreases.

The group of photovoltaic cells for solar energy is called a photovoltaic module. These are coated with a transparent glass or foil with upper and lower enclosure that is encapsulated between the substrate converter and itls electrical connections. The bottom sheet may be transparent, but more often it is a Tedlar plastic. To encapsulate usually it is added thin, transparent sheets of EVA are added, which are merged to create moisture sealing, insulating, transparent and robust.

Photovoltaic modules consist of a network of solar cells as a circuit connected in series to increase the output voltage to the desired value (usually 12V or 14V), while connecting also multiple networks in parallel to increase the electric current to be able to be provided to the device.

The set of photovoltaic modules is called photovoltaic or solar panel or an array. The photovoltaic modules that create an array can be connected to each other in serie, parallel or mixed, to obtain the voltage required by the system (Fig. 2.1.1.2). This makes photovoltaic systems to be able to suit any installation, large or small.

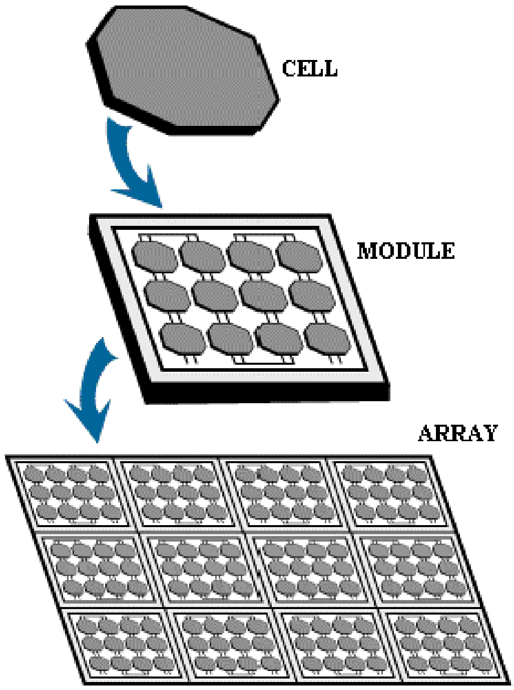


Figure 2.1.1.2-. Photovoltaic array

The type of power they provide is direct current (DC), so if you need alternating current (AC) or increase the voltage, it will have to be added an inverter and/or a power converter.

For the installation of these panels it should be taken several considerations. First of all, is to be noted that throughout the year, the angle of sunlight varies, and that is why we must ensure that the direction of the light vector is parallel to normal vector of the panels. Thus, in the southern hemisphere, the panels are mounted facing true north with an inclination to the horizon that corresponds to the angle to obtain the maximum gain in the winter, while in the northern hemisphere, the panels are oriented towards the geographical south.

The panels can be mounted on the roof of a house or any suitable structure. The place to be chosen should be free of any shadow. This would reduce significantly the performance of the panel. As a general rule, the panels are oriented so that the collecting surface is perpendicular to the midday sun for the month in which maximum gain is desired, depending on the latitude and longitude of the place of implantation. Thus, the amount of daily energy provided by solar panels varies depending on the orientation, location, climate and season.

In addition, the panels must be installed with a minimum distance from any area of approximately 5 cm to permit an adequate airflow through the bottom, which prevents overheating that could reduce their performance (Fig. 2.1.1.3).

Another factor that might reduce its performance is dirt, since it makes difficult the incidence of sunlight. So while photovoltaic modules require little maintenance, it is needed a periodic cleaning. The intensity of the effect depends on the opacity of the waste, so the layers of dust reduce the intensity of solar radiation in a uniform way, they are not dangerous and the power reduction is not usually significant, while the waste from the birds show more serious problem. The action of rain may in many cases reduce the need for cleaning the photovoltaic modules. The cleaning operation is simply washing with treated water modules and a mild detergent. Not considering these general rules, can reduce the efficiency of the system, and even reduce the lifetime of the equipment.

Figure 2.1.1.3-. Photovoltaic modules

ELECTRICAL CHARACTERISTICS

The electrical parameters that characterize the photovoltaic modules are described below.

- **Short circuit current (I_{SC}):** Maximum amount of current that can deliver the PV module under *standard conditions* *, corresponding to zero voltage and therefore no power.
- **Open circuit voltage (V_{OC}):** The maximum voltage that is delivered in a PV module under *standard conditions* *, not allowing any current flow between the terminals of photovoltaic module under conditions of zero current and therefore no power.
- **Maximum or peak power (P_{Max}):** The maximum value of power that can be delivered by the PV module under *standard conditions* *. Its value is specified by a pair of voltage and current values, ranging between 0 and I_{SC} and between 0 and V_{OC}, respectively, for which their product is maximum. This value is provided by the manufacturer to compare and analyze the panels.
- **Current at maximum power**: current delivered to the device at maximum power under *standard conditions* *. It is used as nominal current of the photovoltaic module.
- **Voltage at maximum power:** voltage delivered by the device when the power reaches its maximum value under *standard conditions* *. It is used as a nominal voltage of the device.
- **Maximum system voltage:** The maximum voltage that can be subjected photovoltaic cells of the system.
- **Form factor (FF):** The ratio between maximum power that can be delivered to a load and the product of the open circuit voltage (V_{OC}) and short circuit current (I_{SC}).

$$FF = \frac{I_M \cdot V_M}{V_{OC} \cdot I_{SC}}$$

The *standard conditions**, mentioned before, are defined by the Standard Test Conditions (STC), which is a set of laboratory test conditions which approximate conditions under which solar panels (or photovoltaic modules), might be used to be able to compare different cells and modules with the rated characteristics given by the manufacturer. Standard conditions include three factors:

- Irradiance: sunlight intensity or power striking on a flat surface. The standard measure is 1 kW/m^2.
- Air mass: thickness and clarity of the air through which the sunlight passes to reach the modules. The standard measure is 1,5.
- Cell temperature: Differs from the ambient air temperature. It is defined as 25ºC for the STC.

The above parameters, the electrical characteristics, define the current-voltage characteristic curve (V-I) (Fig 2.1.1.4).

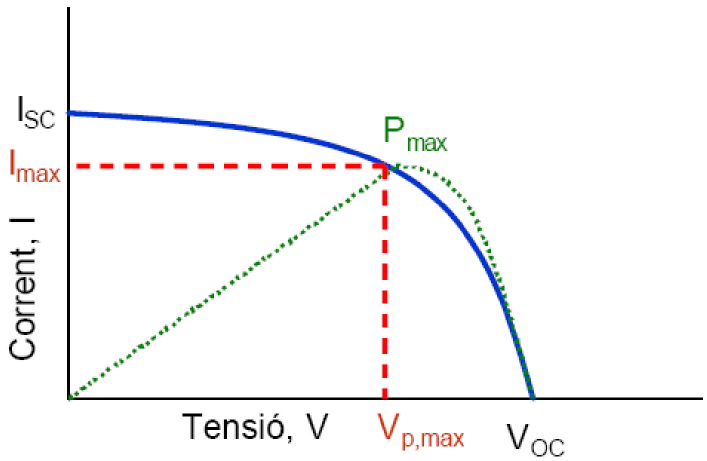


Figure 2.1.1.4 -. Characteristic curve V-I

This characteristic curve is the typical representation of a photovoltaic device (cell, panel, system ...), where one can identify the parameters described above.

These electrical properties are affected by other factors (Fig. 2.1.1.5):

- **Intensity of solar irradiation**: The electricity intensity increases with the intensity of solar radiation. As the current varies in proportion to the solar intensity, the voltage is kept constant.

- **Cell temperature:** The heating of the cells by exposure to sunlight causes a decrease in the voltage generated, and also produces a small increase of intensity for low values of voltage. So, in short, for more high temperatures of the photovoltaic cell, the system performance will be lower.

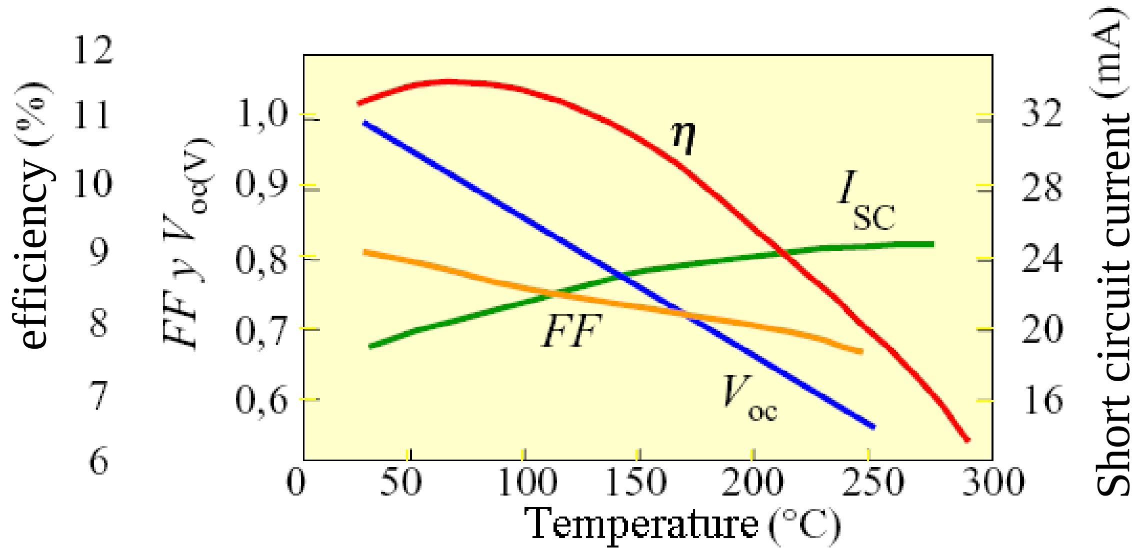


Figure 2.1.1.5-. Influence of FF, V_{OC}, temperature and I_{SC} on efficiency

On figure 2.1.1.5, it can be observed the relation between all the factors explained before and their influence on the performance of the photovoltaic modules.
In summary, the higher number of receptors can be fed with less intensity better (this is achieved by increasing the voltage) due to higher voltage means higher performance.

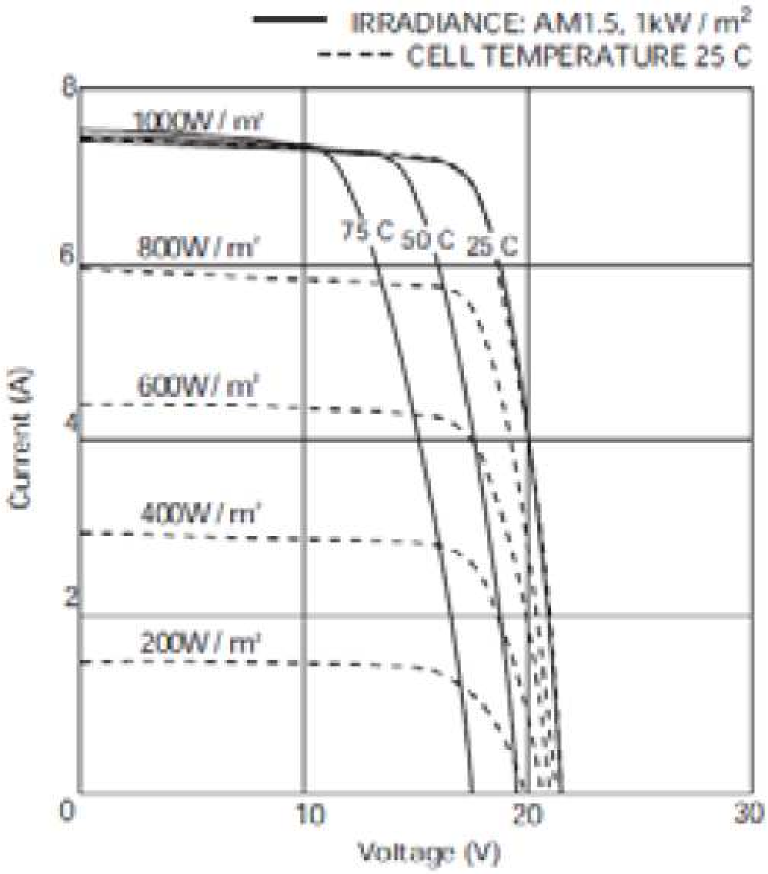


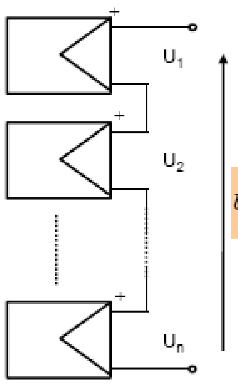
Figure 2.1.1.6-. Influence of temperature and irradiance on curve V-I

It can be also observed (Fig. 2.1.1.6) the relation between current and voltage with the influence of temperature and the irradiance.

The electrical characteristics of the panel or photovoltaic array is the same as those that comprise the module, taking into account the change in power, current and voltage according to the settings made, that is to say, the number of modules connected in series and parallel.

- Modules in series: When photovoltaic modules are connected in series increasing the voltage of the system. The final system voltage is the sum of the individual voltages of each module.

$$V_{total} = V_1 + V_2 + V_3 + \dots + V_n$$

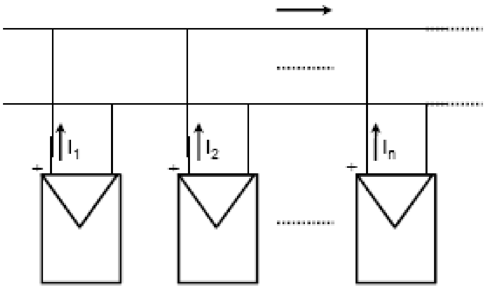


$$U = \sum_{i=1}^{n} U_i$$

- Modules in parallel: Photovoltaic modules are connected in parallel to increase the current of the system. The final current is the sum of the individual currents of each module.

$$I_{total} = I_1 + I_2 + I_3 + \dots + I_n$$

$$I = \sum_{i=1}^{n} I_i$$



In the photovoltaic plants, the modules are connected in serie to increase and achieve the voltage imposed by the inverter chosen, creating an array or string. These strings are afterwards connected in parallel to achieve higher intensity for the system, to get the necessary power.

2.1.2 Storage system (batteries, accumulators)

In an isolated photovoltaic plant, this system is essential, as is the one responsible for storing the DC power produced by the generator to be able to consume while there is no sunlight to generate electricity.

The battery or battery bank is a device capable of converting chemical potential energy into electrical energy. They consist of two electrodes immersed in an electrolyte where chemical reactions occur due to loading or unloading.

If the photovoltaic plant is properly sized, its mission is reliability. Its function is to supply the expected power consumption during periods when there is not enough solar energy to generate electricity in the photovoltaic modules. The sizing of the battery bank is based on the number of days of autonomy without solar radiation desired in the installation.

2.1.3 Control system (Battery charge limit)

The charge controller is an electronic device whose function protects the battery to avoid overcharging or excessive discharge, which can extend the battery life, since the damage may be irreversible. It must ensure that the system operate at maximum efficiency point.

Notice that, this control system is always necessary when using a storage system in the facilities.

2.1.4 Power conversion system (DC-AC inverter)

The function of the inverter or converter is to transform the direct current generated by photovoltaic panels into alternating current, with the magnitude and frequency desired by the user. It can be injected to the electrical grid through their respective transformers used in electrical installations or isolated.

These inverters have a microprocessor to ensure a sinusoidal curve with minimal distortion. Its operating principle is based on the use of electronic devices operating as switches which allows interrupting the current and reverse polarity.

It is important to mention, that the inverters consume electricity while working, and this electricity must be bought to the electrical distributor company, as it is said in the Decree 661/2007.

The main characteristics of an inverter are determined by the input voltage, which must be adapted to the generator, the maximum power that can provide the output waveform, the operating frequency and efficiency, about 85%. This is defined as the ratio between electric power delivered by the inverter to be used (output) and the extracted electricity power of the generator (power input).

Unlike solar panels, an inverter efficiency is not constant and depends on the system load (Fig. 2.1.4.1). For loading rates close to the rated power, efficiency is higher than for low loading rates, as discussed below in the implementation of the studied photovoltaic plant.

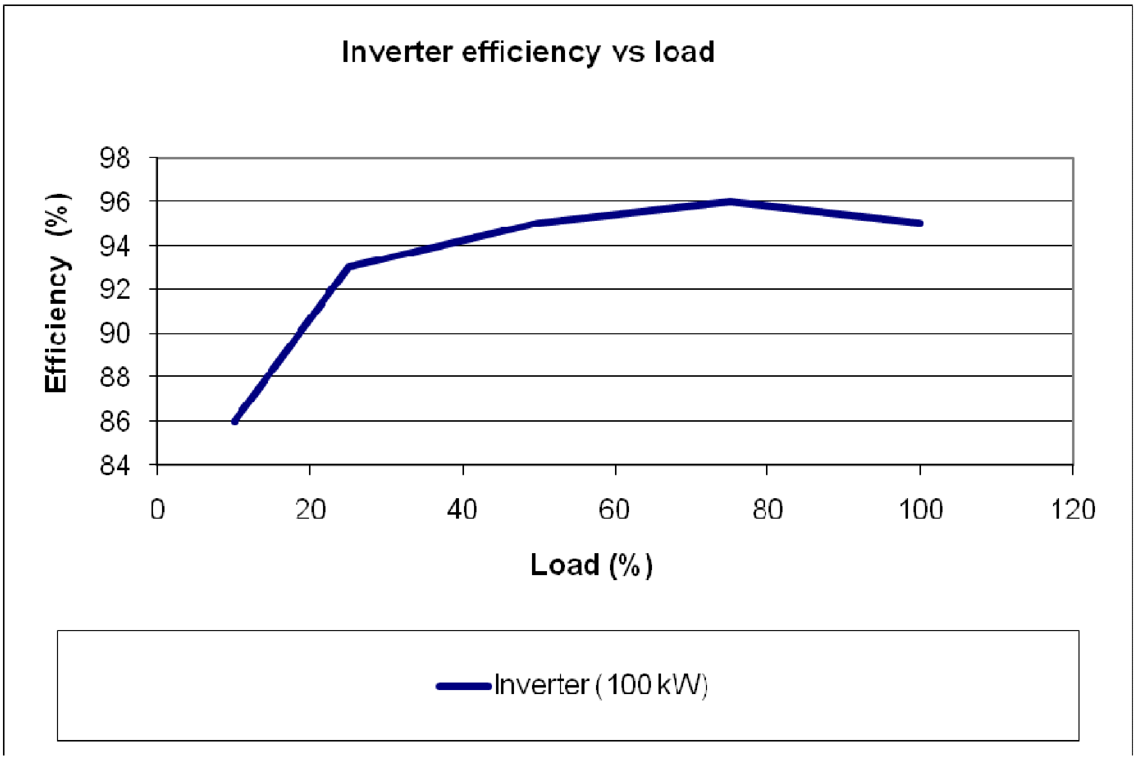


Figure 2.1.4.1-. Efficiency related to the power load supported by the inverter

There are available in the market very different types of inverters, with different degrees of complexity and highly variable performance. Depending on the type of loads to be fed, there can be used very simple inverters, square wave or if so required, sinusoidal wave inverters, more or less sophisticated.

ELECTRICAL CHARACTERISTICS

The electrical parameters that characterize the photovoltaic modules for grid-connected installations, such as the photovoltaic plant that will be discussed later, are listed below.

- Input voltage Vdc
- Inverter power kW
- Output voltage 0,85 – 1 Vac
- Power factor θ > 0,95
- Frequency 50 Hz
- Rate of harmonic distortion (Voltage-current)

2.1.5 Transformation system

Finally, if the aim of the photovoltaic plant is to inject the generated electricity to the electrical grid, it requires a transformation system that raises the voltage of alternating current generated into the voltage of the electricity distribution network, 220 kV, as in the case of the power grid in Spain. For this function the necessary instrument is the electric transformer. Thus, this element will vary the voltage and current of AC input, with constant frequency and power, for ideal machines. It should be noted that in reality the power output will decrease due to different losses.

The operation of a transformer is based on the principle of electromagnetic induction (Fig. 2.1.5.1). It consists of two or more coils of conductive material, electrically isolated from each other usually wound around a common core of ferromagnetic material. The only connection between the coils is the common magnetic flux in the core set. When a coil, primary circuit, is connected to an AC generator, it generates a magnetic flux, which generates in another coil, the secondary circuit, an electromotive force or, what is equal, voltage. Performance under the voltage is determined by the number of turns in the primary or secondary coil as shown below.

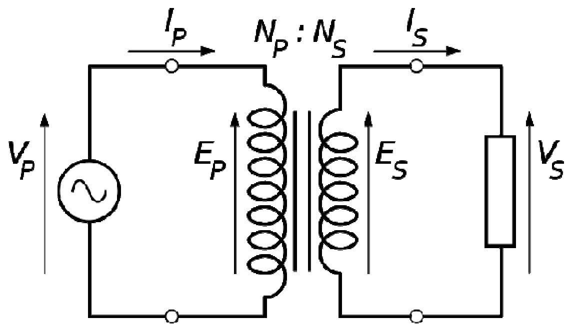


Figure 2.1.5.1-. Principle of electriomagnetic induction in a transformer

Transformers have a high efficiency which is usually about 98%. If we consider the efficiency of 100%, there can be extracted the following equations.

$$\frac{V_p}{V_s} = \frac{I_s}{I_p} = \frac{N_p}{N_s}$$

Where: V_p is the primary alternating voltage

V_s is the output secondary voltage

I_p is the primary input current

I_s secondary output current

N_P is the number of turns in the primary

N_s is the number of turns in the secondary

In these circumstances, the power remains the same:

$$P_p = P_s$$

Where P_p is the primary input power

P_s is the secondary output power

2.2 APPLICATIONS OF SOLAR PHOTOVOLTAIC ENERGY: PHOTOVOLTAIC PLANTS

Photovoltaic solar energy allows a large number of applications because it allows powering off-grid locations, and injecting all the energy produced to the electricity grid for its distribution to the users.

2.2.1 Isolated network with or without accumulation.

In isolated environments, which require little electrical power and network access is difficult, like weather stations or communications repeaters, solar panels are used as a viable economic alternative. To understand the importance of this possibility, it should be noted that approximately one quarter of the world's population lacks an access to electricity.

Because of this, it is commonly applied to feed many devices as autonomous or semi-autonomous items, from watches to satellites, sensors, transmitters and calculators. They can also be examples of rural electrification or isolated dwelling or livestock farm applications, pumping stations, telecommunications repeaters, autonomous lighting, signposting and alarms or other professional applications with the help of storage system if necessary: regulators and batteries.

The process would begin with the generation of energy in photovoltaic modules at low voltages and currents. Next it would go to the battery (or a set of batteries) to be stored, with the previous step by the regulator to avoid damaging the accumulation system. Finally, depending on the required load current, DC or AC, will flow through an inverter, to get the energy in the form desired by the user.

Hence, it can be presented a diagram of the installation depending on the current required: DC or AC (Fig. 2.2.1.1).

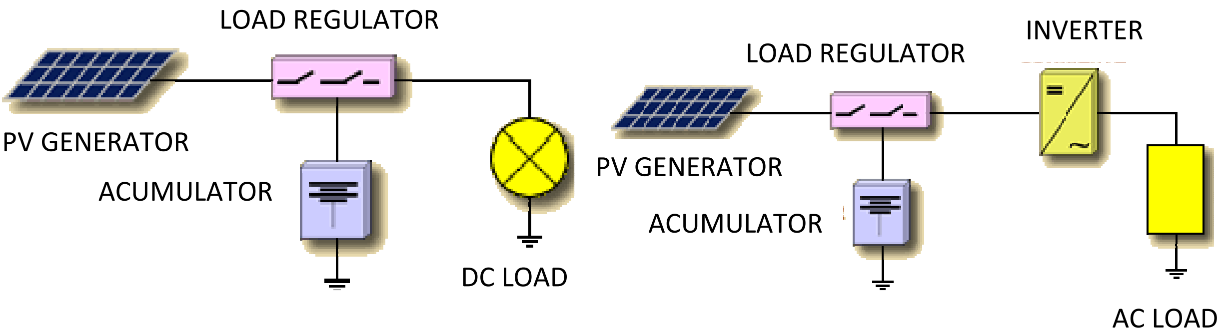


Figure 2.2.1.1-. Scheme of an isolated network: DC or AC load

Currently this system is viable only in buildings without the possibility of connection to the electricity grid because this model increases significantly the return period of the project by the absence of the grant.

2.2.2 Photovoltaic plants connected to the electricity grid

These facilities can be small, associated with domestic consumers and industries, or large photovoltaic plants. In Spain there are even projects up to 48 MW of power. Its function is to provide electricity to the distributor (electrical company) of solar energy. They need a large area to generate enough photovoltaic energy to be contributed to the electrical grid.

The process, simplified, is as follows: energy is generated at low voltages in the photovoltaic modules (380-800 V) and in direct current. Later, it is transformed by an inverter into alternating current. Using a transformer, the voltage is raised to medium voltage (15 or 25 kV) and injected into the distribution grid of the electrical company, previously passing through the production and consumption meter (Fig. 2.2.2.1).

This process driven by the state began in Japan and Germany before arriving in Spain, and is being developed in European countries, USA and many other countries.

Currently, relies on grants to the facility to pursue its growth.

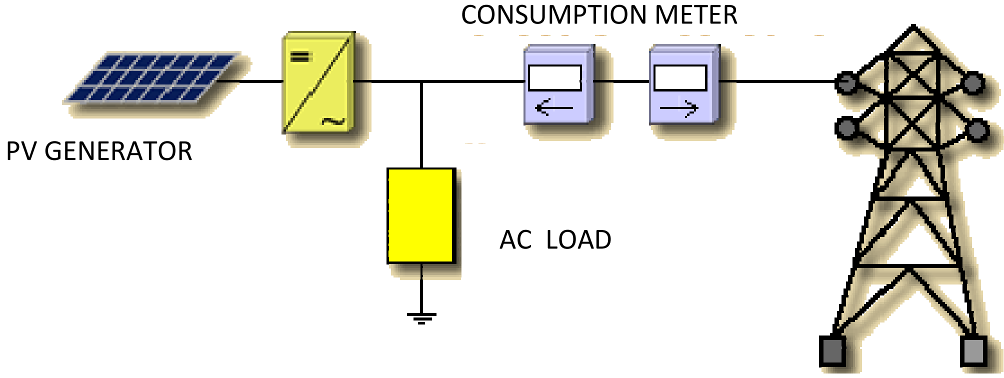


Figure 2.2.2.1-. Scheme of a plant connected to the electrical grid

2.3 ADVANTATGES AND DISADVANTATGES OF SOLAR PHOTOVOLTAIC ENERGY

The advantages and disadvantages that poses the use of solar photovoltaic energy have a positive balance. It has to be considered that we are facing an energy obtained from a free and inexhaustible source, the sun, and it offers good opportunities for business, private and industrial.

It has absolute universality since a photovoltaic plant can be installed anywhere over the Earth and its production will depend on the environmental factors of the area. In addition, as mentioned above, it is capable of providing electricity to all those places where the access to the electricity grid is complicated.

Nowadays, the stronger advantage for humanity is the fact that it is a clean energy. It doesn't emit harmful gases and it avoids CO_2 emissions that would be emitted if instead of generating electricity with photovoltaic technology, it would be generated from fossil fuels. Thus, streamlines the independence of oil imported and avoids territorial disputes caused by the need of oil.

Another positive aspect of this technology is the low maintenance required. As mentioned above, photovoltaic modules also work with both direct and diffuse solar energies on cloudy days.

Finally, it is important to remember that after installing the photovoltaic system, it doesn't require additional investment. If the electricity demand increases, it is simply required to increase the number of photovoltaic modules correctly connected.

The only disadvantage of this technology is precisely the high initial investment to be implemented and the variability of generation due to the variability of the source, since it depends on solar radiation and climate factors.

2.4 LEGISLATION

Photovoltaic systems have to satisfy the regulations of each country where it is installed. In Spain, it should be mentioned the following rules regarding to regarding electricity aspects:

- Law 54/1997 of September 27, regulates the activity in the supply of electricity.
- ECO/797/2002 of March 22, which adopts the procedure of measurement and control of power supply continuity.
- Royal Decree 1955/200 of 1 December. Regulates the transmission, distribution, marketing, supply and authorization procedures for electric power facilities.
- Royal Decree 842/2002. Low voltage electrotechnical regulations.

Regarding to legislation that affects directly to renewable energies, it can be distinguished the following documents:

- Renewable Energy Plan in Spain (PER) 2005-2010. Approved for the purpose of strengthen the priorities of the Spanish government's energy policy, to improve safety and quality of electricity supply and improve environmental respect, together with the determination to fulfill international commitments arising from the Kyoto Protocol and Spain's membership of the European Union to achieve the objectives of the National Allocation Plan allowances of greenhouse gases, 2008-2012.
- Royal Decree 661/2007 of May 25. Regulates the activity of electricity production using renewable energies. It defines the group of especial scheme, billing for active

power, defines the regulated photovoltaic system price according to the group and the supplement for reactive power.

- Royal Decree 1578/2008 of September 26. It sets the remuneration for photovoltaic energy, which establishes variable bonus based on the location of the facility (floor: 0,32 €/ kWh or roof: 0,34 €/ kWh), being subject in addition to a quarterly maximum number of installed power from 2009, to adapt from quarter to quarter depending on market. Note that this regime is only for photovoltaic plants with a final registration after September 2008.
- Royal Decree 1662/2000 of September 29. It concerns the connection of photovoltaic installations to the low voltage network.

3. IMPLEMENTATION OF A PHOTOVOLTAIC PLANT

3.1 LOCATION

The facilities being the subject of this report are located on the roofs of buildings and water tanks on the ground ETAP Aigues Ter Llobregat, located at 4.6 km of the road from Martorell to Olesa de Montserrat, in the TM of Abrera, in Catalonia, Spain (latitude 41º 30’ 25’’, longitude 1º 55’ 2’’). In the figures 3.1.1 to 3.1.3, it is showed a map of the site, which leaves the location completely defined. The central UTM coordinates of the system are: UTM X: 440133; UTM Y: 4595864.

Figure 3.1.1-. Map of the location

Figure 3.1.2-. Satellite map of the location

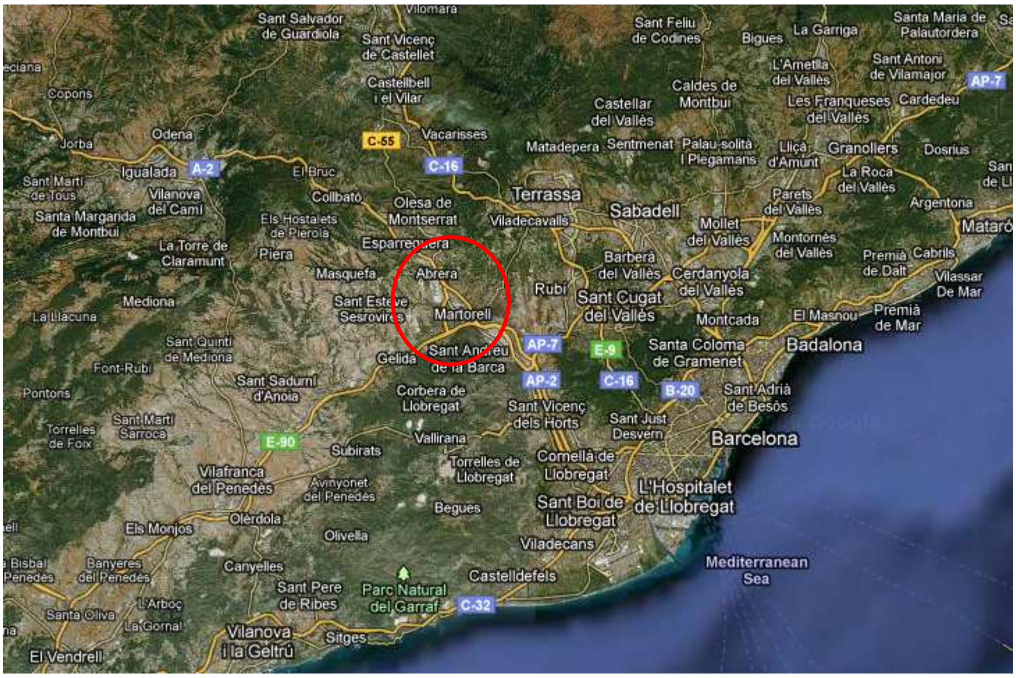


Figure 3.1.3-. Map of the location in Catalonia

3.1.1 State of Solar irradiation in the area

In order to define exhaustively the photovoltaic plant situation object of this project, it is necessary to start showing the radiation that reaches the plant. Keep in mind that these data have been obtained directly from the facilities measured with radiation probes, except the data for the months of January and December 2010, owing to a malfunction of probes, and have been considered radiation from the meteorological central station located in Els Hostalets de Pierola, the nearest one to the facilities.

Due to its geographical situation described above, the photovoltaic modules are oriented towards the south with an inclination of 30 degrees, for maximum benefit of solar irradiation (Fig. 3.1.1.1).

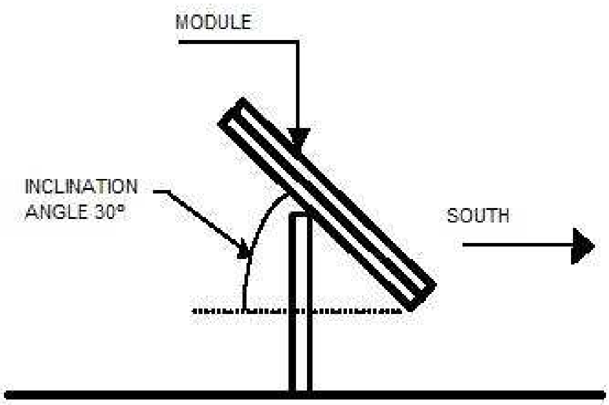


Figure 3.1.1.1-. Orientation and inclination of photovoltaic modules

As a starting point for the later calculations, it has been taken the average daily global solar radiation. From this value, it has been obtained the radiation energy for the entire month. It is important to define that this value of daily irradiation is for the 24 hours of the day and not for the daylight hours.

$$I_m\left({}^{Wh}/_{m^2}\right) = \left(\sum_{month} I_d\left({}^{W}/_{m^2}\right)\right) \cdot 24\left({}^{h}/_{day}\right)$$

Where:

- I_m is the monthly average solar radiation energy received by the photovoltaic modules with an angle of 30º.
- I_d is the average daily solar radiation, obtained directly from the facilities, received by the photovoltaic modules with an angle of 30º.

From this value, it can be calculated the operational value of the equivalent peak hours (HSP). This parameter indicates how many hours a month the modules receive $1000 \, W/m^2$. Therefore, from these equivalent peak hours it can be calculated the energy generated by the photovoltaic module, using the specifications given by the manufacturer where all the nominal characteristics are given for a radiation of $1000 \, W/m^2$.

$$HSP(h) = \frac{I_m\left(Wh/m^2\right)}{E\left(W/m^2\right)}$$

Where:

- HSP equivalent peak hours received by the photovoltaic plant monthly.
- I_m is the monthly average solar radiation energy received by the photovoltaic modules with an angle of 30º
- E is the standard solar irradiance of $1000 \, W/m^2$.

Thus, the average monthly radiation calculated set out below (Table 3.1.1.1, Fig. 3.1.1.2) and the equivalent peak hours are the data from which have been made all subsequent theoretical calculations.

P.V. Abrera 2010														
STARTING BASES	Units	January	February	March	April	May	June	July	August	September	October	November	December	Total
Average daily irradiation *(Id)*	W/m2	88,87	128,81	194,53	213,42	233,17	249,75	258,32	243,65	194,05	178,54	144,95	101,54	185,80
Irradation without inclination (0º) *(Im)*	Wh/m2	57.262,83	74.960,79	125.339,68	133.077,38	150.239,66	155.731,17	166.443,91	156.989,16	121.000,53	115.036,85	90.384,80	65.422,38	1.411.889,14
Irradation with inclination (30º) *(Im)*	Wh/m2	66.121,41	86.557,26	144.729,78	153.664,51	173.481,80	179.822,86	192.192,86	181.275,46	139.719,37	132.833,10	104.367,37	75.543,25	1.630.309,05
Equivalent peak hours *(HSP)*	h	66,12	86,56	144,73	153,66	173,48	179,82	192,19	181,28	139,72	132,83	104,37	75,54	1630,31

Table 3.1.1.1-. Starting bases: Average daily irradiation, monthly irradiation (0º and 30º) and equivalent peak hours

As it has been discussed before, the photovoltaic modules inclination affects the incident radiation. To be able to compare it, it has been calculated the radiation that would arrive if the inclination was of 0º, with the following equation:

$$E_{rad\,0º} = E_{rad\,30º} \cdot \cos 30º$$

So, it can be proved that if the PV modules were at 0º, the solar energy received would be much lower than with the proper inclination for the area for the implementation of the plant. It shows that it is necessary to tilt the PV modules to obtain maximum benefit from solar energy.

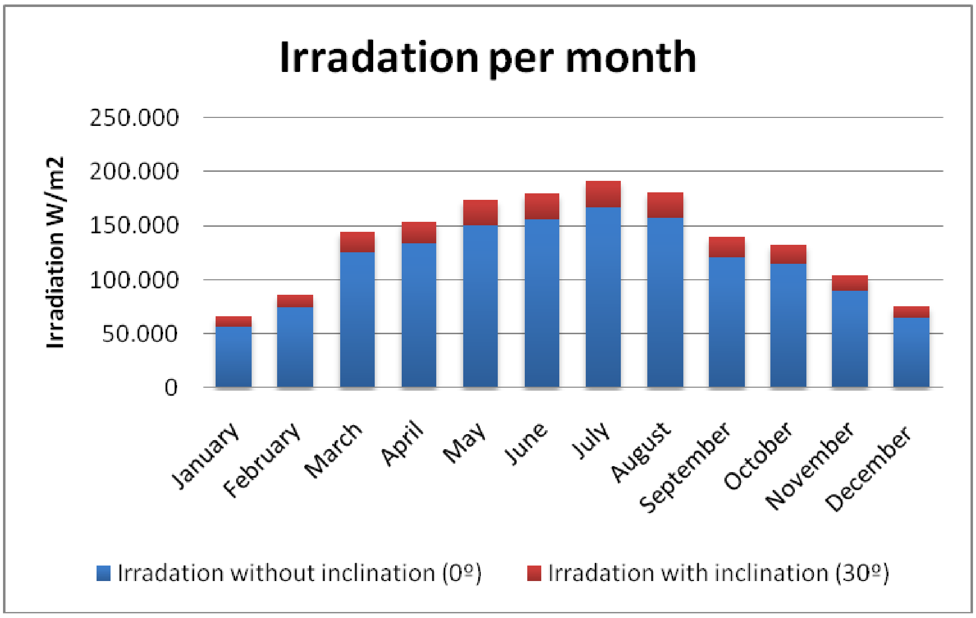


Figure 3.1.1.2-. Evolution of the irradiation per month (0º and 30º)

As it can be seen in the graph (Fig.3.1.1.2), for the months of the greatest radiation, as are the months of May, June, July and August, the difference to the inclinations is also greater than during the rest of the year. It can also be observed the solar radiation distribution during the year 2010, which as it might be expected, in the summer months is higher than in the winter months, due to the higher number of sunlight hours in during the summer.

Below (Fig.3.1.1.3) it is shown the evolution of the equivalent peak hours for the year 2010, proportional to the radiation shown in the previous graph.

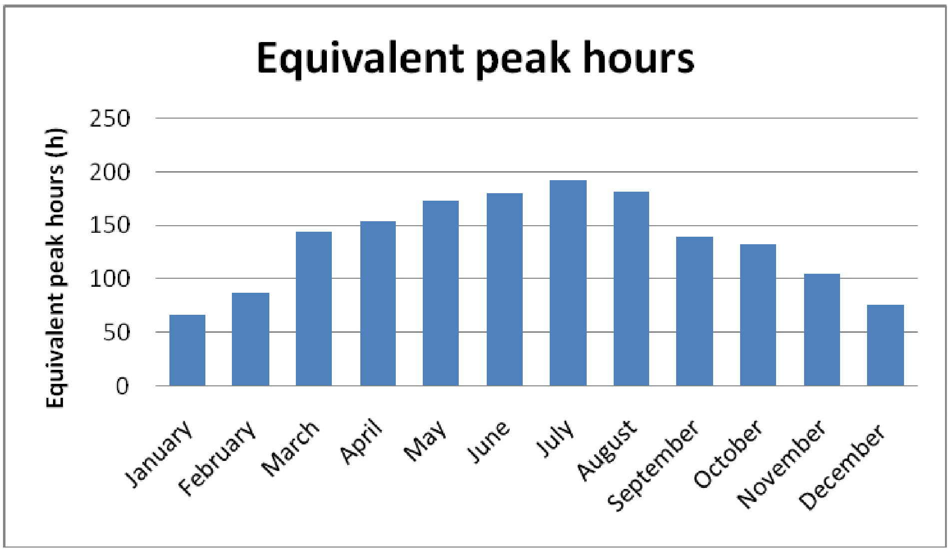


Figure 3.1.1.3-. Equivalent peak hours (HSP) per month

In the figure 3.1.1.4, it is shown the daily evolution of solar radiation for a day chosen at random.

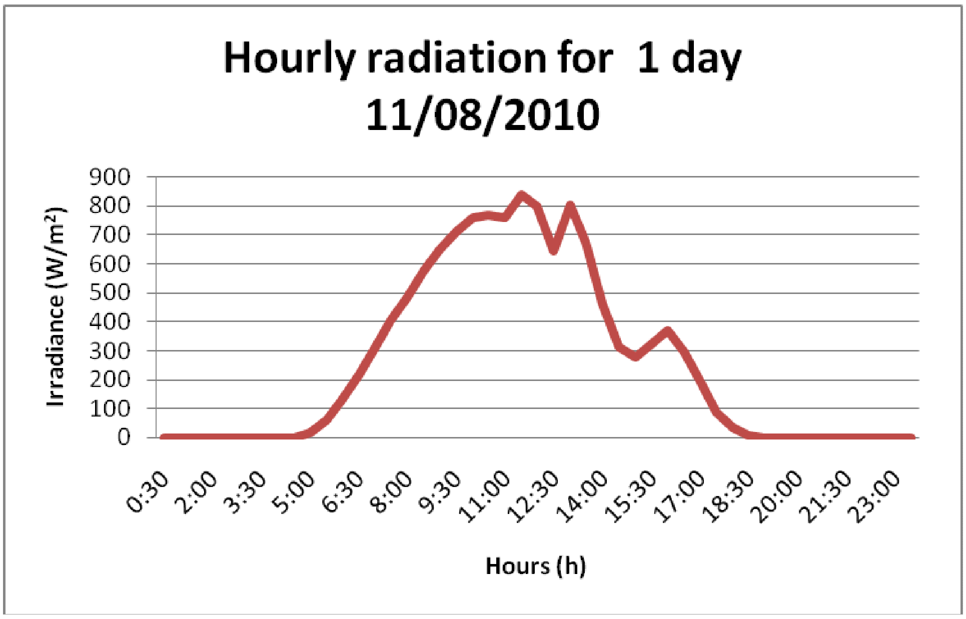


Figure 3.1.1.4-. Hourly radiation for 1 day (11/08/2010)

It is interesting to observe the solar radiation distribution during a typical day chosen at random. It has been chosen a day of August (Fig. 3.1.1.4) because it is a month with a high radiation, with more sunlight hours. It can be noted in this solar radiation distribution, that the most sunlight hours are between 8 am and 14 pm, in the summer of 2010.

3.2 GENERAL DESCRIPTION OF THE PHOTOVOLTAIC PLANT

The photovoltaic generator consists of a series of interconnected modules, which is responsible for transforming the sun power into electrical power. However, this energy is in form of direct current (DC) and must be transformed by the inverter into alternate current (AC) to fit the conventional network. In the particular case of the installation in question, the photovoltaic generator is connected to the medium voltage network of the company ENDESA DISTRIBUCIÓN ELÉCTRICA, SA. To be able to connect to the grid, relevant considerations regarding the interconnection has been taken into account, under current legislation.

Thus, the photovoltaic modules generate a direct current proportional to the solar irradiance that incises on them. This current is conducted to the inverter which, using the power technology, converts it into alternating current at the same frequency as the power grid to be available to any user. This energy generated, measured with the corresponding meter, will be sold to the distributor as it says the Royal Decree 661/2007.

The project presented below fulfills all technical considerations required in the decree of September 12, 1985, which is complemented with the above mentioned and sets out the basic administrative and technical conditions of connection to the medium voltage grid of the photovoltaic facilities.

Currently, the photovoltaic generator of the plant consists of 15 929 modules, which can be divided into 15 725 modules of 175 Wp and 204 modules of 170 Wp. Among the whole system, it reaches a total power of 2 786,56 kWp.

In the table 3.2.1 there is a summary table with all the elements of the installation.

The electricity generated by the whole photovoltaic plant is exported to the 25 kV network. All the self-powered elements of the plant are fed from the purchased electricity, as it is stipulated by the Royal Decree 661 of 25 May 2007. The equipment that consumes electricity consists of:

- Inverters
- Illumination
- Ventilation
- Control System

The electricity billing is done based on readings made from a meter. It measures both the electricity exported to the grill and the electricity consumed.

In the figure 3.2.1, it is shown an electric scheme of the plant, with indication where is located each equipment. The numbers between the boxes indicate the number of elements that are connected in series. Each box is connected to their respective strings. Each string consists of 17 modules. To describe more clearly the number of boxes, strings and modules there are attached the tables 3.2.2 to 3.2.6, indicating the number of elements in series and the installed power for each category.

Table 3.2.1-. Elements of the photovoltaic plant

STARTING BASES	UNITS	VALUE
Photovoltaic modules		
175 Wp modules		
Number of modules	nº	15.725
Nominal power	Wp	175
Installed power	kWp	2.752
170 Wp modules		
Number of modules	nº	204
Nominal power	Wp	170
Installed power	kWp	35
Total number of modules	nº	15.929
Total installed power modules	kWp	2.787
Inverters		
323 kW inverters		
Number of inverters	nº	8
Nominal power	kW	323
Available power	kW	2.584
100 kW inverters		
Number of inverters	nº	2
Nominal power	kW	100
Available power	kW	200
Total number of inverters	nº	10
Total available power inverters	kW	2.784
Transformers		
630 kVA transformers		
Number of transformers	nº	1
Nominal power	kVA	630
Available power	kVA	630
800 kVA transformers		
Number of transformers	nº	3
Nominal power	kVA	800
Available power	kVA	2.400
400 kVA transformers		
Number of transformers	nº	1
Nominal power	kVA	400
Available power	kVA	400
Total number of transformers	nº	5
Total available power transformers	kVA	3.430

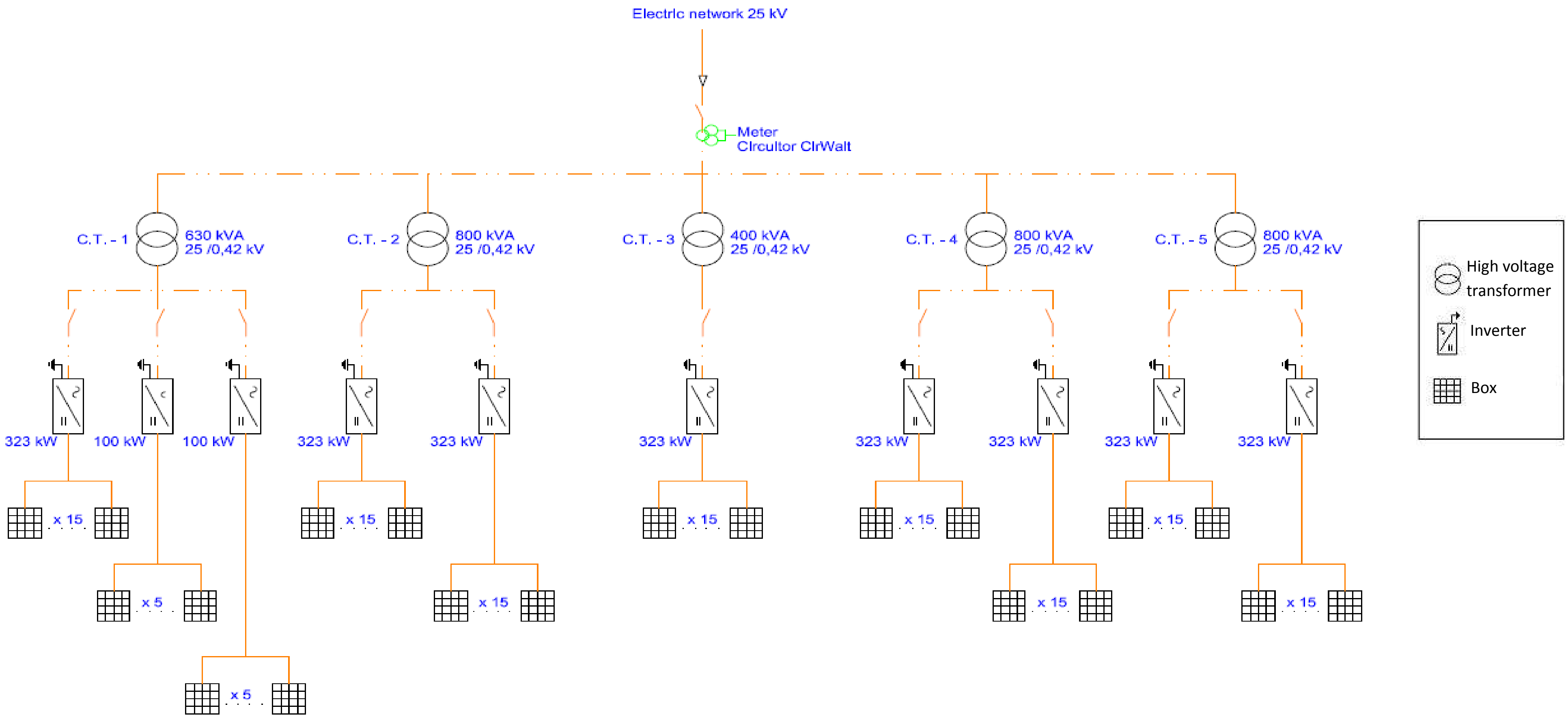


Figure 3.2.1-. Electric scheme of the Abrera photovoltaic plant

Table 3.2.2-. Description of the electric scheme: boxes in C.T.1

P.V. ABRERA			
Equipment	**Nº of Strings**	**Nº of modules**	**Power (kW)**
Scheme P.V. Abrera			
C.T. 1			
INV 1 (323 kW)			
Box 1	8	136	23,8
Box 2	8	136	23,8
Box 3	8	136	23,8
Box 4	8	136	23,8
Box 5	8	136	23,8
Box 6	8	136	23,8
Box 7	8	136	23,8
Box 8	8	136	23,8
Box 9	8	136	23,8
Box 10	8	136	23,8
Box 11	8	136	23,8
Box 12	8	136	23,8
Box 13	6	102	17,85
Box 14	5	85	14,875
Box 15	5	85	14,875
Total INV 1 C.T. 1	**112**	**1904**	**333,2**
INV 2 (100 kW)			
Box 1	8	136	23,8
Box 2	8	136	23,8
Box 3	8	136	23,8
Box 4	8	136	23,8
Box 5	3	51	8,925
Total INV 2 C.T. 1	**35**	**595**	**104,125**
INV 3 (100 kW)			
Box 1	8	136	23,8
Box 2	5	85	14,875
Box 3	4	68	11,9
Box 4	8	136	23,12
Box 5	4	68	11,56
Total INV 3 C.T. 1	**29**	**493**	**85,255**
Total C. T. 1	**176**	**2992**	**522,58**

Table 3.2.3-. Description of the electric scheme: boxes in C.T.2

P.V. ABRERA			
Equipment	**Nº of Strings**	**Nº of modules**	**Power (kW)**
C.T. 2			
INV 1 (323 kW)			
Box 1	8	136	23,8
Box 2	8	136	23,8
Box 3	8	136	23,8
Box 4	8	136	23,8
Box 5	8	136	23,8
Box 6	8	136	23,8
Box 7	8	136	23,8
Box 8	8	136	23,8
Box 9	8	136	23,8
Box 10	8	136	23,8
Box 11	8	136	23,8
Box 12	8	136	23,8
Box 13	4	68	11,9
Box 14	4	68	11,9
Box 15	4	68	11,9
Total INV 1 C.T. 2	**108**	**1836**	**321,3**
INV 2 (323 kW)			
Box 1	8	136	23,8
Box 2	8	136	23,8
Box 3	8	136	23,8
Box 4	8	136	23,8
Box 5	8	136	23,8
Box 6	8	136	23,8
Box 7	8	136	23,8
Box 8	8	136	23,8
Box 9	8	136	23,8
Box 10	8	136	23,8
Box 11	8	136	23,8
Box 12	8	136	23,8
Box 13	5	85	14,875
Box 14	5	85	14,875
Box 15	5	85	14,875
Total INV 2 C.T. 2	**111**	**1887**	**330,225**
Total C. T. 2	**219**	**3723**	**651,525**

Table 3.2.4-. Description of the electric scheme: boxes in C.T.3 and C.T.4

P.V. ABRERA			
Equipment	**Nº of Strings**	**Nº of modules**	**Power (kW)**
C.T. 3			
INV 1 (323 kW)			
Box 1	8	136	23,8
Box 2	8	136	23,8
Box 3	8	136	23,8
Box 4	8	136	23,8
Box 5	8	136	23,8
Box 6	8	136	23,8
Box 7	8	136	23,8
Box 8	8	136	23,8
Box 9	8	136	23,8
Box 10	8	136	23,8
Box 11	8	136	23,8
Box 12	8	136	23,8
Box 13	4	68	11,9
Box 14	4	68	11,9
Box 15	4	68	11,9
Total INV 1 C.T. 3	**108**	**1836**	**321,3**
Total C. T. 3	**108**	**1836**	**321,3**
C.T. 4			
INV 1 (323 kW)			
Box 1	8	136	23,8
Box 2	8	136	23,8
Box 3	8	136	23,8
Box 4	8	136	23,8
Box 5	8	136	23,8
Box 6	8	136	23,8
Box 7	8	136	23,8
Box 8	8	136	23,8
Box 9	8	136	23,8
Box 10	8	136	23,8
Box 11	8	136	23,8
Box 12	8	136	23,8
Box 13	4	68	11,9
Box 14	4	68	11,9
Box 15	4	68	11,9
Total INV 1 C.T. 4	**108**	**1836**	**321,3**

Table 3.2.5-. Description of the electric scheme: boxes in C.T.4 and C.T.5

P.V. ABRERA			
Equipment	**Nº of Strings**	**Nº of modules**	**Power (kW)**
INV 2 (323 kW)			
Box 1	8	136	23,8
Box 2	8	136	23,8
Box 3	8	136	23,8
Box 4	8	136	23,8
Box 5	8	136	23,8
Box 6	8	136	23,8
Box 7	8	136	23,8
Box 8	8	136	23,8
Box 9	8	136	23,8
Box 10	8	136	23,8
Box 11	8	136	23,8
Box 12	8	136	23,8
Box 13	4	68	11,9
Box 14	4	68	11,9
Box 15	4	68	11,9
Total INV 2 C.T. 4	**108**	**1836**	**321,3**
Total C. T. 4	**216**	**3672**	**642,6**
C.T. 5			
INV 1 (323 kW)			
Box 1	8	136	23,8
Box 2	8	136	23,8
Box 3	8	136	23,8
Box 4	8	136	23,8
Box 5	8	136	23,8
Box 6	8	136	23,8
Box 7	8	136	23,8
Box 8	8	136	23,8
Box 9	8	136	23,8
Box 10	8	136	23,8
Box 11	8	136	23,8
Box 12	8	136	23,8
Box 13	5	85	14,875
Box 14	4	68	11,9
Box 15	4	68	11,9
Total INV 1 C.T. 5	**109**	**1853**	**324,275**

Table 3.2.6-. Description of the electric scheme: boxes in C.T.5

P.V. ABRERA			
Equipment	**Nº of Strings**	**Nº of modules**	**Power (kW)**
INV 2 (323 kW)			
Box 1	8	136	23,8
Box 2	8	136	23,8
Box 3	8	136	23,8
Box 4	8	136	23,8
Box 5	8	136	23,8
Box 6	8	136	23,8
Box 7	8	136	23,8
Box 8	8	136	23,8
Box 9	8	136	23,8
Box 10	8	136	23,8
Box 11	8	136	23,8
Box 12	8	136	23,8
Box 13	5	85	14,875
Box 14	4	68	11,9
Box 15	4	68	11,9
Total INV 2 C.T. 5	**109**	**1853**	**324,275**
Total C. T. 5	**218**	**3706**	**648,55**
Total photovoltaic plant	**937**	**15929**	**2786,555**

The presented tables 3.2.2 to 3.2.6 show that not all the equipments are installed to work on the same load. In the case of the inverters and the transformers, this parameter is very important as it affects directly on their efficiency and consequently on the overall efficiency of the photovoltaic plant.

The following table (table 3.2.7) shows the percentage of design load of each equipment element, calculated from its respective nominal power. As we can see, some of the inverters are overloaded. At first sight, it could be thought that is a mistake, but afterwards it will be shown that this overload, even more, is necessary, to ensure a high efficiency due to the losses that here haven’t been covered.

P.V. ABRERA			
Equipment	Nominal power (kW)	Installed power (kW)	Load percentage (%)
INVERTER			
Inverterr 1 C.T. 1	323	333,2	103,16%
Inverter 2 C.T. 1	100	104,125	104,13%
Inverter 3 C.T. 1	100	85,255	85,26%
Inverter 1 C.T. 2	323	321,3	99,47%
Inverter 2 C.T. 2	323	330,225	102,24%
Inverter 1 C.T. 3	323	321,3	99,47%
Inverter 1 C.T. 4	323	321,3	99,47%
Inverter 2 C.T. 4	323	321,3	99,47%
Inverter 1 C.T. 5	323	324,275	100,39%
Inverter 2 C.T. 5	323	324,275	100,39%
TRANSFORMER			
C.T. 1	630	522,58	82,95%
C.T. 2	800	651,525	81,44%
C.T. 3	400	321,3	80,33%
C.T. 4	800	642,6	80,33%
C.T. 5	800	648,55	81,07%

Table 3.2.7-. Percentage of design load of each element

In the next point, it is described in detail all the technical specifications of the main equipment of the installation. In this section, it will be analyzed how these loads affects the efficiency of each element.

3.2.1 Photovoltaic modules

As mentioned above, the photovoltaic panels are responsible for converting the solar energy from the absorbed radiation into electrical energy in DC. Here are the most important technical characteristics of the two models of photovoltaic panels installed in the photovoltaic plant in Abrera.

The modules used in this plant have the following characteristics:

· *170W modules:*

Cell technology: Monocrystalline

Manufacturer: SUNFLOWER CORPORATION

Module title: SF170-M

- PHYSICAL CHARACTERISTICS OF THE MODULE
  - Width (mm) 808
  - Height (mm) 1.580
  - Thickness (mm) 35
  - Weight (Kg) 16

- MODULE ELECTRICAL CHARACTERISTICS
  - Nominal power (Wp) 170
  - Short circuit current ISC(A) 5,2
  - Current at rated operating voltage IPMax (A) 4,88
  - Open circuit voltage VOC (V) 43,4
  - Operating voltage VPMax (V) 34,8
  - Temperature coefficients
    - Power (%/ºC) -0,5 (±0,05)
    - Intensity (%/ºC) +0,06 (±0,01)
    - Voltage (mA/ºC) -158 (±10)

· *175W modules:*

Cell technology: Monocrystalline

Manufacturer: SUNFLOWER CORPORATION

Module title: SF175-M

- PHYSICAL CHARACTERISTICS OF THE MODULE
  - Width (mm) 808
  - Height (mm) 1.580
  - Thickness (mm) 35
  - Weight (Kg) 16

- MODULE ELECTRICAL CHARACTERISTICS
  - Nominal power (Wp) 175
  - Short circuit current ISC(A) 5,30
  - Current at rated operating voltage IPMax (A) 5
  - Open circuit voltage UOC (V) 43,7
  - Operating voltage UPMax (V) 35
  - Temperature coefficients
    - Power (%/ºC) -0,5 (±0,05)
    - Intensity (%/ºC) +0,06 (±0,01)
    - Voltage (mA/ºC) -158 (±10)

It is interesting to note that the manufacturing technology of these modules must pass a rigorous approval tests which ensure great resistance to weathering and a high insulation between electrically active parts and accessible externally.

To sumarize, the solar generator of the installation generates 2 786,56 Wp. Below, in table 3.2.1.1, it is related the electrical characteristics of each one of these branches of 17 modules in series for 170 and 175Wp modules (table 3.2.1.1):

	Modules 170 W_P	Modules 175 W_P
Short Circuit Current ISC(A)	5,20	5,30
Current at rated operating voltage IPMax (A)	4,88	5
Open circuit voltage UOC (V) (STC)	737,8	742,9
Operating voltage UPMax (V) (STC)	578	595
Number of modules in series	17	17

Table 3.2.1.1-. Electrical characteristics of 17 modules in series for 170 and 175 Wp

The output power of the photovoltaic panels is directly related to the global irradiation, the cells temperature and the dirt. For temperatures exceeding 25 ºC, the output power of the panel decreases compared to the nominal power, proportionally to the increase of the cell temperature.

The equation that defines the temperature losses is:

If (Tc > 25º) ➔ $Losses(\%) = G \cdot (T_c - 25)$

If (Tc ≤ 25º) ➔ $Losses(\%) = 0$

T_c variable is the photovoltaic cells temperature which is obtained with the following equation:

$$T_c = T_a + \frac{TONC - 20}{800} \cdot G$$

The variables are presented in the table 3.2.1.2.

Variable analysis		
Variable		**Units**
Tc	Cell temperature	ºC
Ta	Daytime temperature	ºC
G	Solar irradiance	W/m2
TONC	Nominal operating temperature of the module	ºC

Table 3.2.1.2- Temperature variables of photovoltaic modules

In the case of the dirt factor, due to the weather, pollution and the influence of animals, it is generated a layer in the surface of the photovoltaic modules that reduces the incident irradiation that gets to the modules. These losses can be closer to 5 % during the lifetime of the modules.

So, in summary, during the energy balance of the whole plant, it will be taken into account both power losses due to the temperature of the cells and the dirt factor.

Figure 3.2.1.1-. 170Wp string of photovoltaic modules

3.2.2 Inverters

The inverters of this installation work by their DC side connected to a photovoltaic generator, while by the AC side are connected to a transformer that adapts the inverter output voltage, 400V (three phase), to the network, 3x400/230V. The logical control used, guarantees in addition a full automatic mode, synchronization with the network, tracking the maximum power point (MPP) and to avoid any lost during the period of rest (Stand-By).

The inverter is capable to transform alternating current and deliver to the network all the power generated by the photovoltaic generator at every moment, working from a solar radiation threshold.

The inverters are responsible for transforming the DC electricity from the photovoltaic panels into AC electricity to be sent to each transformer. The same inverters have a microprocessor, explained in the previous section, responsible for ensuring a sinusoidal wave with minimal distortion. It also incorporates batteries to regulate the power factor according to the needs.

The inverters installed in this plant have the following characteristics:

INVERTER NOMINAL POWER 323 kW

Brand SIEMENS

Model SINVERT SOLAR

- PHYSICAL CHARACTERISTICS OF THE INVERTER
  - Width (mm) 2700
  - Height (mm) 2000
  - Thickness (mm) 800
  - Weight (Kg) 2025

- ELECTRICAL CHARACTERISTICS OF THE INVERTER
  - Input Voltage Rank 450 -- 750 VDC
  - Maximum Output Voltage DC 900 VDC
  - Maximum Input Current DC 820A (250A each input)
  - Nominal Output Power 323 kVA
  - Maximum Output Power 357 kVA
  - Network Voltage 3x400 V
  - Frequency 50 or 60Hz ±2%
  - Maximum Distortion AC current injected into network < 3,0 %

Efficiency		
100% of load	%	96
75% of load	%	96
50% of load	%	96
25% of load	%	94
10% of load	%	89

INVERTER RATED NOMINAL 100 kW

Brand SIEMENS

Model SINVERT SOLAR

- PHYSICAL CHARACTERISTICS OF THE INVERTER
  - Width (mm) 918
  - Height (mm) 1902
  - Thickness (mm) 834
  - Weight (Kg) 850

- ELECTRICAL CHARACTERISTICS OF THE INVERTER
  - Input Voltage Rank 450 -- 750 VDC
  - Maximum Output Voltage DC 900 VDC
  - Maximum Input Current DC 231A (80A each input)
  - Nominal Output Power 100 kVA
  - Maximum Output Power 105 kVA
  - Network Voltage 3x400 V
  - Frequency 50 o 60Hz ±2%
  - Maximum Distortion AC current injected into network < 3,0 %

Efficiency		
100% of load	%	95
75% of load	%	96
50% of load	%	95
25% of load	%	93
10% of load	%	86

As it can be seen in the previous specifications, the efficiency of inverters is directly related to the power load. This concept has great relevance during the design stage to achieve the maximum efficiency.

The following chart (figure 3.2.2.1) describes the evolution of efficiency related to the power load supported of each inverter model.

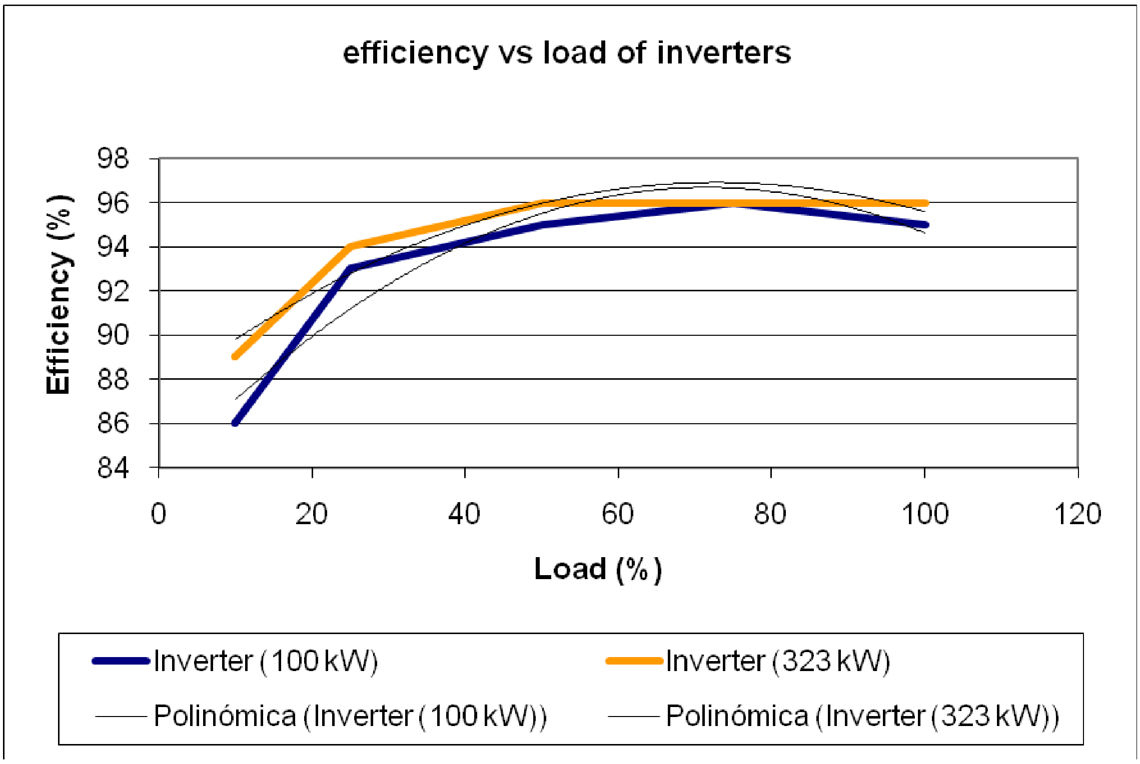


Figure 3.2.2.1-. Evolution of efficiency related to the power load supported if each inverter model

From the presented efficiency graph, it can be obtained the equations of efficiency according to the load for each inverter can be obtained:

Inverter (100 kW) ➔ $y = -0{,}0025x^2 + 0{,}3634x + 83{,}681$

Inverter (323 kW) ➔ $y = -0{,}0018x^2 + 0{,}2622x + 87{,}348$

Where ‘y’ represents a efficiency for a given load ‘x’. With these equations it will be possible to know the specific efficiency of an inverter for any load.

From the above efficiency equations and the nominal powers of the modules connected to each inverter, the theoretical design efficiencies for each one can be calculated:

DESIGN EFFICIENCY		
Inverter	**Load (%)**	**Efficiency (%)**
Inverter 1 C.T. 1	103,16%	95,24
Inverter 2 C.T. 1	104,13%	94,41
Inverter 3 C.T. 1	85,26%	96,49
Inverter 1 C.T. 2	99,47%	95,62
Inverter 2 C.T. 2	102,24%	95,34
Inverter 1 C.T. 3	99,47%	95,62
Inverter 1 C.T. 4	99,47%	95,62
Inverter 2 C.T. 4	99,47%	95,62
Inverter 1 C.T. 5	100,39%	95,53
Inverter 2 C.T. 5	100,39%	95,53

Table 3.2.2.1-. Theoretical design efficiencies for each inverter

Basing on the table 3.2.2.1, it can be observed efficiency values about 95% of the inverters under nominal conditions. For the stand point of design, and considering that very few hours a year modules give their nominal power, it would be better to overload these inverters to get higher efficiencies under normal conditions. Later, it will be shown that these inverters have pretty significant losses under normal conditions.

3.2.3 Transformers

The transformers are responsible for transforming the 420V voltage of the inverters into a 25.000V voltage to be able to do the interconnection with the distribution grid of ENDESA DISTRIBUCIÓ ELECTRICA S.A.

Each transformation center has a power transformer. The main characteristics of each transformer given by the manufacturer are the following ones (table 3.2.3.1 to 3.2.3.3):

TRANSFORMER 1 – Isolated oil phase transformer

(Transformer of the CT1)

Transformer (630 kVA)		
Brand		COTRADIS
Rule		UNE 21.428
Nominal power	kVA	630
Primary voltage	V	25000
Secondary voltage	V	420
Connection group		Dyn 11
Losses in hollow	W	1450
Load losses	W	6650
Frequency	Hz	50
Refrigeration		ONAN
Dimensions		
Height	mm	995
Width	mm	1510
Thickness	mm	910
Efficiency (cos θ = 1)		
100% of load	%	98,73
75% of load	%	98,91
50% of load	%	99,02
25% of load	%	98,83

Table 3.2.3.1-. 630 kVA transformer

TRANSFORMER 2 – Isolated oil phase transformer

(Transformer of the CT3)

Transformer (400 kVA)		
Brand		COTRADIS
Rule		UNE 21.428
Nominal power	kVA	400
Primary voltage	V	25000
Secondary voltage	V	420
Connection group		Dyn 11
Losses in hollow	W	1120
Load losses	W	4900
Frequency	Hz	50
Refrigeration		ONAN
Dimensions		
Height	mm	910
Width	mm	1430
Thickness	mm	890
Efficiency (cos θ = 1)		
100% of load	%	98,51
75% of load	%	98,72
50% of load	%	98,84
25% of load	%	98,59

Table 3.2.3.2-. 400 kVA transformer

TRANSFORMER 3 – Isolated oil phase transformer

(Transformer of the CT2, CT4 and CT5)

Transformer (800 kVA)		
Brand		COTRADIS
Rule		UNE 21.428
Nominal power	kVA	800
Primary voltage	V	25000
Secondary voltage	V	420
Connection group		Dyn 11
Losses in hollow	W	1700
Load losses	W	8500
Frequency	Hz	50
Refrigeration		ONAN
Dimensions		
Height	mm	1010
Width	mm	1780
Thickness	mm	1080
Efficiency (cos θ = 1)		
100% of load	%	98,78
75% of load	%	98,97
50% of load	%	99,09
25% of load	%	98,89

Table 3.2.3.3-. 800 kVA transformer

As it has been shown in previous schemes, the overall photovoltaic plant consists of 5 transformers in 5 transformation centers (CT) located throughout the plant.

In the same way that for the inverters, for transformers their efficiency is directly related with its working load.

Below (fig. 3.2.3.1), it is shown the graph of efficiency for each of the transformers depending on the operational load, extracting the equation for later calculations.

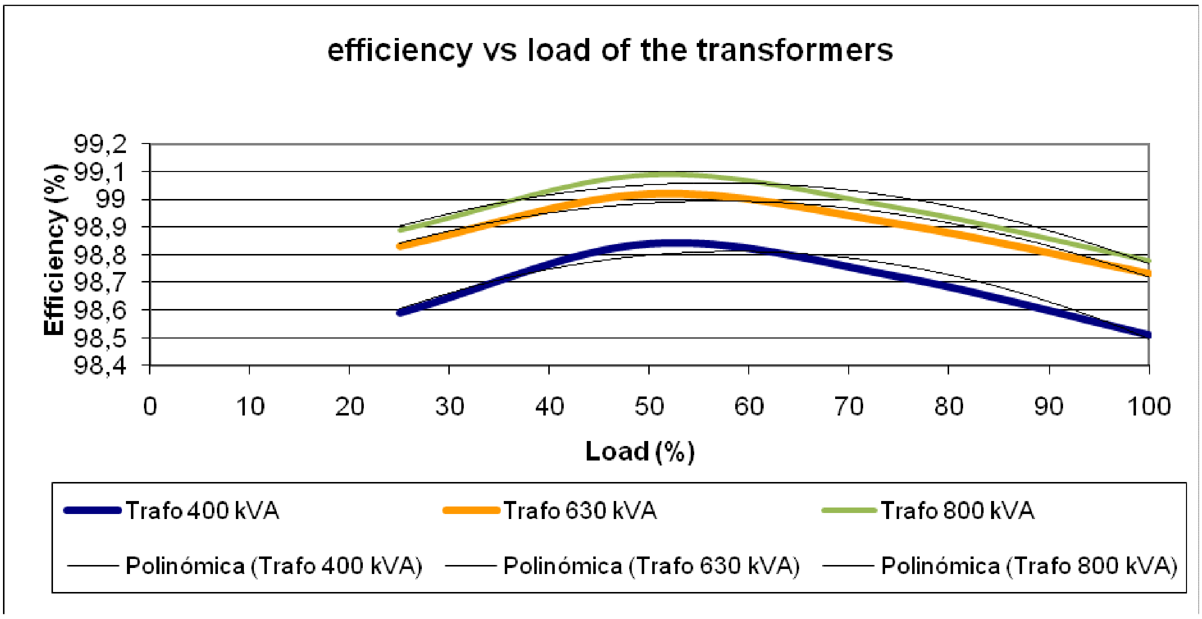


Figure 3.2.3.1-. Efficiency for each of the transformers depending on the operational load

From the graph above (fig. 3.2.3.1), it can be obtained the equation based on the efficiency for each operational load for each transformer.

Transformer (400 kVA) ➔ $y = -0,0002x^2 + 0,0216x + 98,18$

Transformer (630 kVA) ➔ $y = -0,0001x^2 + 0,0169x + 98,512$

Transformer (800 kVA) ➔ $y = -0,0002x^2 + 0,0177x + 98,557$

Where ‘y’ represents a efficiency for a given load ‘x’. With these equations it will be possible to know the specific efficiency of a transformer for any load given.

Having the above efficiency equations, it can be obtained the real design efficiencies based on the installed power and the designed load supported (table 3.2.3.4).

DESIGN EFFICIENCY		
Transformer	**Load (%)**	**Efficiency (%)**
Tr. 630 kVA C.T.1	82,95%	99,23
Tr. 800 kVA C.T.2	81,44%	98,67
Tr. 400 kVA C.T.3	80,33%	98,62
Tr. 800 kVA C.T.4	80,33%	98,69
Tr. 800 kVA C.T.5	81,07%	98,68

Table 3.2.3.4-. Real design efficiencies based on installed power and the designed load supported

Very high efficiencies with very low sensibility to the load percentage can be observed. It can be deduced that the transformers won't affect substantially to the overall efficiency of the photovoltaic plant studied, as it will be demonstrated later on the analysis.

3.3 THEORETICAL ANALYSIS OF THE DIFFERENT ENERGETIC EFFICIENCIES AND ECONOMICS.

3.3.1 Starting data

To proceed with the calculation of electricity production, CO_2 emissions avoided and energetic remuneration, it has been created a mathematical model that permit the comparison of the theoretical generation values with the real ones obtained from the electrical company's bills throughout the whole year 2010 for the photovoltaic plant object of this project.

First of all, the starting data (table 3.3.1.1 and 3.3.1.2) have been raised as the meteorological data of the photovoltaic plant over the year 2010. As explained before, irradiation has been obtained directly from radiation probes installed in the facilities, except for the data of January and December that have been extracted from the meteorological station of Els Hostalets de Pierola, due to the malfunction of the radiation probes those months.

Table 3.3.1.1-. Starting data for the modeling concept

CONCEPT		
Nominal power plant	kW	2786,555
CO_2 ratio	g CO_2/kWh	411,5
Unit price of electricity sale	€/MWh	441,69
Theoretical modules efficiency	%	14

Table 3.3.1.2-. Meteorological starting data

P.V. Abrera 2010														
	Units	January	February	March	April	May	June	July	August	September	October	November	December	Total
STARTING BASES														
Irradation without inclination (0º) *(Im)*	Wh/m2	57.262,83	74.960,79	125.339,68	133.077,38	150.239,66	155.731,17	166.443,91	156.989,16	121.000,53	115.036,85	90.384,80	65.422,38	1.411.889,14
Irradation with inclination (30º) *(Im)*	Wh/m2	66.121,41	86.557,26	144.729,78	153.664,51	173.481,80	179.822,86	192.192,86	181.275,46	139.719,37	132.833,10	104.367,37	75.543,25	1.630.309,05
Average daytime solar power *(G)*	W/m2	213,29	257,61	389,06	365,87	349,76	374,63	387,49	417,69	332,67	357,08	347,89	243,69	4.036,72
Equivalent peak hours *(HSP)*	h	66,12	86,56	144,73	153,66	173,48	179,82	192,19	181,28	139,72	132,83	104,37	75,54	1630,31
Average daytime temperature *(Ta)*	ºC	10,24	10,99	12,91	14,34	18,34	22,47	24,35	25,60	21,83	18,72	15,61	11,66	17,25
Average temperature photovoltaic cell *(Tc)*	ºC	18,24	20,65	27,50	28,06	31,45	36,52	38,88	41,26	34,31	32,11	28,65	20,80	29,87
Days per month *(dm)*	nº	31	28	31	30	31	30	31	31	30	31	30	31	365
Solar hours per day *(hs)*	h	10	12	12	14	16	16	16	14	14	12	10	10	13

The irradiation in the table 3.3.1.2 corresponds to the monthly average radiation incident on the surface of a module with the proper orientation, south, and inclination of 0º and 30º, respectively.

In order to obtain, later, the working load closest to the real one of each element, it is very important to calculate the average irradiation for each month in accordance to the hours of sunlight daily that the PV modules will receive energy from the sun. Thus, irradiation will not be distributed during the 24 hours a day, but, in fact, it will be divided by the average of solar hours available for each month, because it is evident that irradiation over the night is 0 W/m^2. Thereby, it will be possible to calculate the average power in its working range.

Thus, with this irradiation shown in the table above with the modules inclined 30º, which is the inclination of the modules in the photovoltaic plant object of this study, and knowing the days of each month and the daily average sunlight hours per month, it can be obtained the average daytime solar power:

$$G\left({}^{W}\!/_{m^2}\right) = \frac{I_m \left({}^{Wh}\!/_{m^2}\right)}{d_M\,(days) \cdot h_s \left({}^{h}\!/_{day}\right)}$$

Where,

- G is the average daytime solar power.
- I_m is the monthly average solar radiation energy received by the photovoltaic modules with an angle of 30º.
- d_m are the days per month.
- h_s is the daily average sunlight hours for each month.

Once calculated the average daytime solar power that strikes over the photovoltaic modules, it can be calculated the energy obtained from the photovoltaic generator, which is not the irradiation received directly from the sun.

When estimating the theoretical output power of the photovoltaic panels, it is necessary to calculate the losses due to the temperature of the modules and the dirt factor.

The energy production of the photovoltaic modules is intimately linked with the daytime temperature and the temperature of the photovoltaic cells. From the data of the incident radiation on the modules and the average daytime temperature per month, it is calculated the temperature of a photovoltaic cell:

$$T_c\,(ºC) = T_a\,(ºC) + \frac{TONC\,(ºC) - 20\,(ºC)}{800\,\left(W/_{m^2}\right)} \cdot G\left(W/_{m^2}\right)$$

Where,

- G is the average daytime solar power.
- T_c is the temperature of a photovoltaic cell.
- T_a is the average daytime temperature per month.
- TONC Nominal operating temperature of the module under certain conditions: 800 W/m^2 and 20 ºC.

This temperature of the photovoltaic cell permits to continue the calculating of the losses of the solar modules due to the temperature reached by the PV cells and it is calculated as follows:

If (Tc > 25º) ➔ $losses(\%) = G \cdot (T_c - 25)$

If (Tc ≤ 25º) ➔ $losses(\%) = 0$

As for the dirt losses generated by the photovoltaic modules, after consulting various websites (i.e. greenrhinoenergy.com) where the dirt losses considered were 3, 4 and 5%, it has been considerate for this photovoltaic plant losses of a 5% monthly, approximately.

The following table 3.3.1.3, shows the photovoltaic modules efficiencies due to the temperature and dirt losses of the PV cells.

Table 3.3.1.3-. Modules efficiencies

P.V. Abrera 2010														
Modules efficiencies	**Units**	**January**	**February**	**March**	**April**	**May**	**June**	**July**	**August**	**September**	**October**	**November**	**December**	**Total**
Temperature efficiency *(αt)*	%	100,00%	100,00%	98,90%	98,65%	97,15%	94,92%	93,88%	92,83%	95,89%	96,87%	98,39%	100,00%	97,29%
Dirtiness efficiency *(αb)*	%	95,00%	95,00%	95,00%	95,00%	95,00%	95,00%	95,00%	95,00%	95,00%	95,00%	95,00%	95,00%	95,00%

As shown in the table 3.3.1.3 and graphs below (fig. 3.3.1.1 and fig. 3.3.1.2), the efficiencies due to the cells temperature decrease when the temperature increases. The losses increase with temperature, being maxima in the hottest month of the year. During January, February and December, the temperature of the cell does not affect to the efficiency because the average temperature of the cells don't reach the monthly average of 25ºC,thus its losses in this months due to temperature are null.

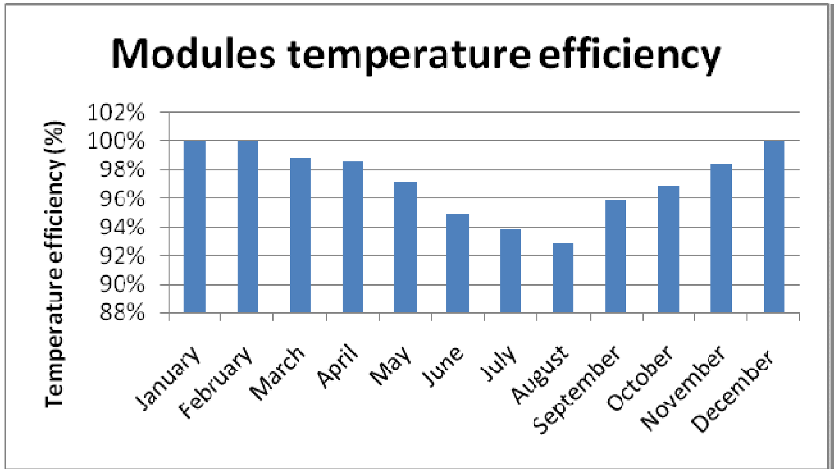


Figure 3.3.1.1-. Modules temperature efficiencies

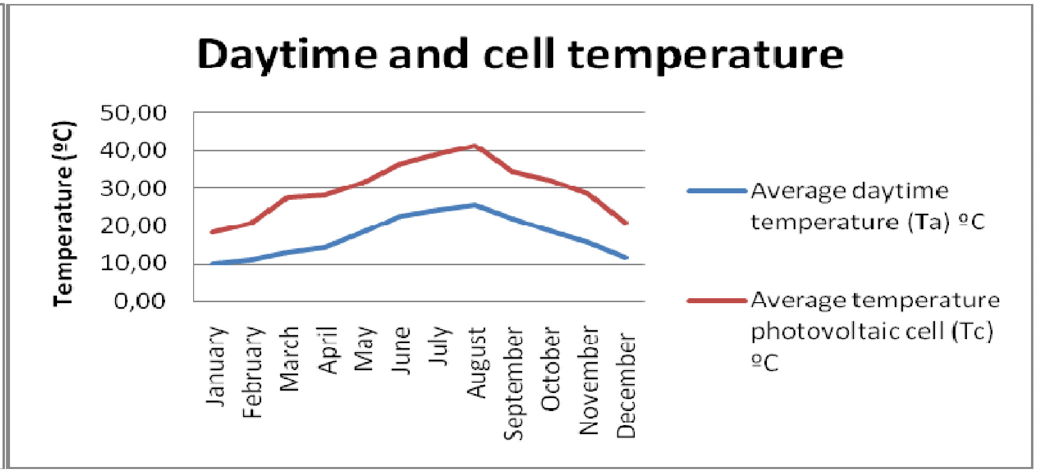


Figure 3.3.1.2-. Daytime and cell temperature

3.3.2 Theoretical load for each element

As we know, to find the efficiency of the photovoltaic plant and of each element, we need to find the loads they are subjected during their operation hours. For this purpose, it is necessary to calculate, previously the average output power of the plant. From the data obtained in previous sections, it can be calculated as follows:

$$P_s(kW) = \frac{G\left({}^{W}/_{m^2}\right) \cdot \alpha_{Ts} \cdot \alpha_d \cdot P_N(kW)}{E\left({}^{W}/_{m^2}\right)}$$

Where,

- P_s is the average output power of the photovoltaic plant.
- G is the average daytime solar power.
- α_{Ts} is the efficiency of the PV modules due to the losses caused by the cells temperature.
- α_d is the efficiency of the PV modules due to the losses caused by the cells dirtiness.
- $P_N(kW)$ is the nominal power of the PV plant.
- E is the standard solar irradiance of 1000 ${}^{W}/_{m^2}$.

Now, with these values it can be calculated the load percentage that supports the whole PV plant and each one of the inverters and transformers, with the purpose to be able later to calculate their respective efficiencies:

$$Plant\ load(\%) = \frac{P_s(kW)}{P_N(kW)} \cdot 100$$

$$Element\ load(\%) = \frac{P_{ix}(kW)}{P_{Nx}(kW)} \cdot 100$$

Where,

- P_s is the average output power of the photovoltaic plant.
- $P_N(kW)$ is the nominal power of the PV plant.
- $P_{ix}(kW)$ is the output power of each element.
- $P_{Nx}(kW)$ is the nominal power of each element.

Below (table 3.3.2.1), it is shown the average output theoretical power of the plant and the theoretical load of the PV plant and each one of the inverters and transformers, obtained from the solar irradiation data given with the equations explained above.

P.V. Abrera 2010														
	Units	January	February	March	April	May	June	July	August	September	October	November	December	Total
PERCENTAGE LOAD FOR EACH ELEMENT														
Average output power of the PV plant *(Ps)*	KW	564,64	681,95	1018,57	955,46	899,55	941,36	962,97	1026,43	844,49	915,64	906,11	645,10	863,52
Plant load percentage	%	20,26	24,47	36,55	34,29	32,28	33,78	34,56	36,83	30,31	32,86	32,52	23,15	30,99
Load percentage INV. 1 C.T. 1	%	20,90	25,25	37,71	35,37	33,30	34,85	35,65	38,00	31,26	33,90	33,54	23,88	31,97
Load percentage INV. 2 C.T. 1	%	21,10	25,48	38,06	35,70	33,61	35,18	35,98	38,35	31,56	34,21	33,86	24,11	32,27
Load percentage INV. 3 C.T. 1	%	17,28	20,86	31,16	29,23	27,52	28,80	29,46	31,40	25,84	28,01	27,72	19,74	26,42
Load percentage INV 1 C.T. 2	%	20,16	24,34	36,36	34,11	32,11	33,60	34,38	36,64	30,15	32,69	32,35	23,03	30,83
Load percentage INV 2 C.T. 2	%	20,72	25,02	37,37	35,06	33,00	34,54	35,33	37,66	30,98	33,59	33,24	23,67	31,68
Load percentage INV 1 C.T. 3	%	20,16	24,34	36,36	34,11	32,11	33,60	34,38	36,64	30,15	32,69	32,35	23,03	30,83
Load percentage INV 1 C.T. 4	%	20,16	24,34	36,36	34,11	32,11	33,60	34,38	36,64	30,15	32,69	32,35	23,03	30,83
Load percentage INV 2 C.T. 4	%	20,16	24,34	36,36	34,11	32,11	33,60	34,38	36,64	30,15	32,69	32,35	23,03	30,83
Load percentage INV 1 C.T. 5	%	20,34	24,57	36,70	34,42	32,41	33,92	34,69	36,98	30,43	32,99	32,65	23,24	31,11
Load percentage INV 2 C.T. 5	%	20,34	24,57	36,70	34,42	32,41	33,92	34,69	36,98	30,43	32,99	32,65	23,24	31,11
Load percentage C.T. 1	%	16,81	20,30	30,32	28,44	26,78	28,02	28,67	30,55	25,14	27,26	26,97	19,20	25,71
Load percentage C.T. 2	%	16,50	19,93	29,77	27,92	26,29	27,51	28,14	30,00	24,68	26,76	26,48	18,85	25,24
Load percentage C.T. 3	%	16,28	19,66	29,36	27,54	25,93	27,14	27,76	29,59	24,34	26,39	26,12	18,60	24,89
Load percentage C.T. 4	%	16,28	19,66	29,36	27,54	25,93	27,14	27,76	29,59	24,34	26,39	26,12	18,60	24,89
Load percentage C.T. 5	%	16,43	19,84	29,63	27,80	26,17	27,39	28,02	29,86	24,57	26,64	26,36	18,77	25,12

Table 3.3.2.1-. Percentage load for each element

In this table 3.3.2.1, it can be observed that for any month, neither inverters nor transformers get to a 50% of its partial load, very beneath its optimum point.

Below (fig. 3.3.2.1 and 3.3.2.2), there is a comparison of one of the inverters and one of the transformers with their optimal loading rate for working at maximum efficiency.

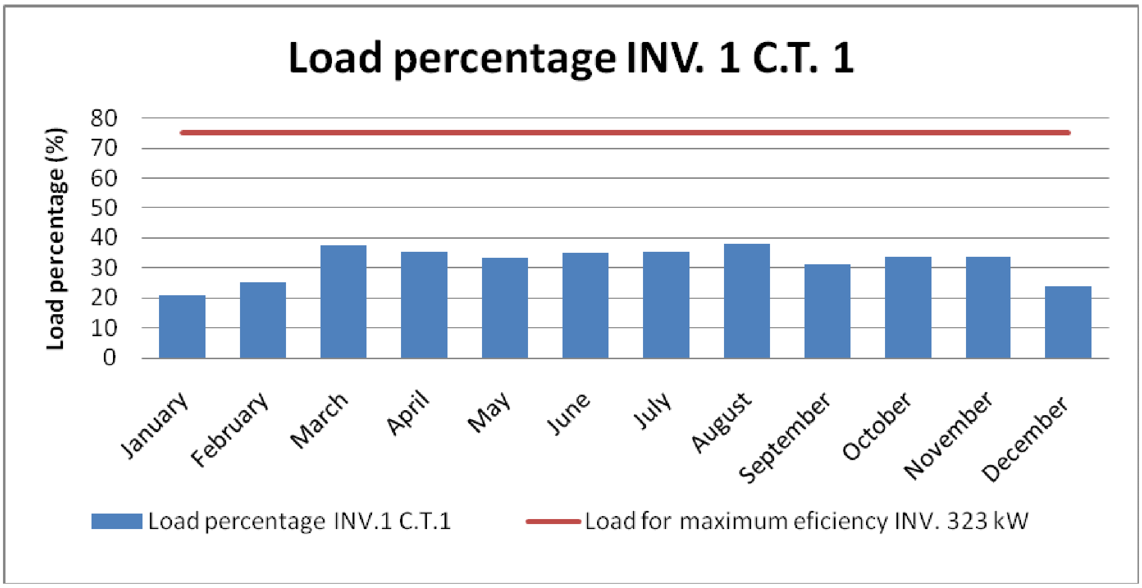


Figure 3.3.2.1-. Load percentage of the inverter 1 of C.T.1

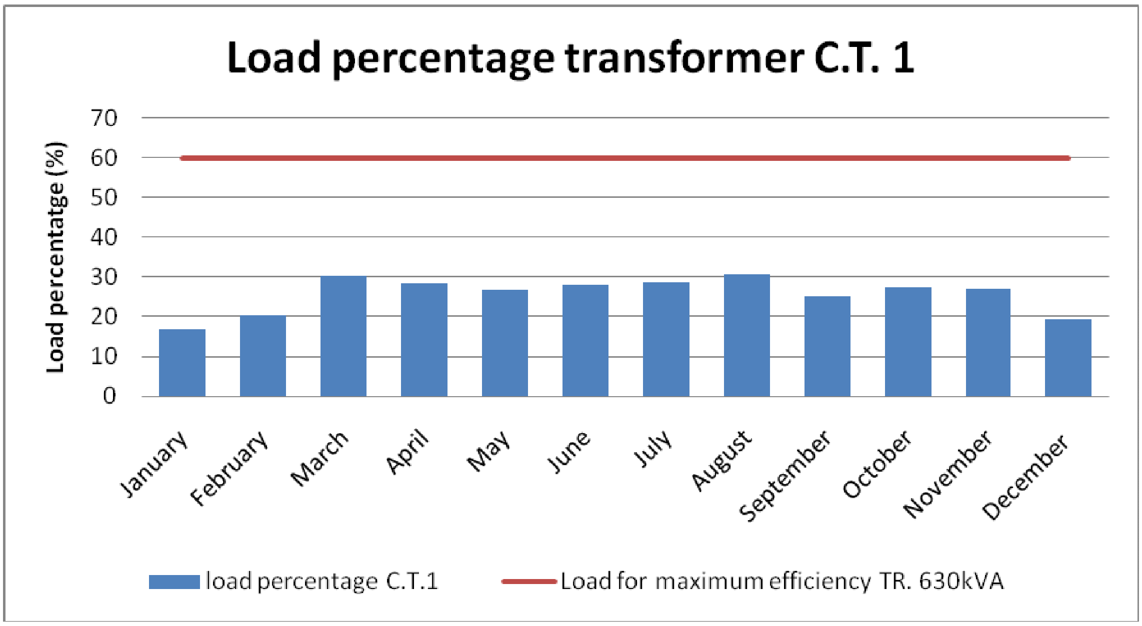


Figure 3.3.2.2-. Load percentage of the transformer of C.T.1

As it can be observed, the partial loads of the elements are well below the optimal load for the maximum efficiency, 75% for the 323 kW inverter and 60% for the 630 kVA transformer according to the graphs presented in the specifications. This may be due to the fact that the photovoltaic modules almost never work at their nominal power, so in consequence, it will never be obtained the power for which have been sized the plant. Thus, this difference may be caused by losses in the elements and an incorrect design of the plant.

To achieve the maximum power it should be increased the number of modules connected to each inverter in the design phase. This will increase the partial load of each element making it to approach the optimum load. Later, it will be discussed how the load affects to the efficiency of each element.

3.3.3 Theoretical efficiency of each element

From the above calculated working loads for each inverter and transformer it has been calculated the efficiency for each one depending on the incident radiation on the PV plant, with the equations previously described in the specifications of the items.

Inverter (100 kW) ➔ $y = -0{,}0025x^2 + 0{,}3634x + 83{,}681$

Inverter (323 kW) ➔ $y = -0{,}0018x^2 + 0{,}2622x + 87{,}348$

Transformer (400 kVA) ➔ $y = -0{,}0002x^2 + 0{,}0216x + 98{,}18$

Transformer (630 kVA) ➔ $y = -0{,}0001x^2 + 0{,}0169x + 98{,}512$

Transformer (800 kVA) ➔ $y = -0{,}0002x^2 + 0{,}0177x + 98{,}557$

It has to be clear that I am always calculating theoretical values based on the radiation given in order to compare them later with the real ones.

Below it is the table with all theoretical efficiencies of the elements of the plant (table 3.3.1). Note that it has been taken into account the losses generated in the wiring of both DC and AC.

These values have been approximated as follows separating between DC and AC:

- For DC it has been considered the losses between strings and boxes, and between boxes and inverters of 0,44% and 1,26%, respectively. So, for DC wiring it has been considered a total of 1,7% of losses.
- For AC it has been considered the losses between inverters and transformation centre, and between transformation centre and the meter of the electrical company of 0,2% and 0,012%, respectively. So, for AC wiring it has been considered a total of 0,21% of losses.

Table 3.3.3.1-. Energetic performances for each element

P.V. Abrera 2010														
	Units	January	February	March	April	May	June	July	August	September	October	November	December	Total
ENERGETIC PERFORMANCES														
Inverters performances														
Inversor 1 C.T. 1	%	92,04%	92,82%	94,68%	94,37%	94,08%	94,30%	94,41%	94,71%	93,79%	94,17%	94,12%	92,58%	93,84%
Inversor 2 C.T. 1	%	90,24%	91,32%	93,89%	93,47%	93,07%	93,37%	93,52%	93,94%	92,66%	93,19%	93,12%	90,99%	92,73%
Inversor 3 C.T. 1	%	89,21%	90,17%	92,58%	92,17%	91,79%	92,07%	92,22%	92,63%	91,40%	91,90%	91,83%	89,88%	91,49%
Inversor 1 C.T. 2	%	91,90%	92,66%	94,50%	94,20%	93,91%	94,13%	94,23%	94,54%	93,62%	94,00%	93,95%	92,43%	93,67%
Inversor 2 C.T. 2	%	92,01%	92,78%	94,63%	94,33%	94,04%	94,26%	94,36%	94,67%	93,74%	94,12%	94,08%	92,55%	93,80%
Inversor 1 C.T. 3	%	91,90%	92,66%	94,50%	94,20%	93,91%	94,13%	94,23%	94,54%	93,62%	94,00%	93,95%	92,43%	93,67%
Inversor 1 C.T. 4	%	91,90%	92,66%	94,50%	94,20%	93,91%	94,13%	94,23%	94,54%	93,62%	94,00%	93,95%	92,43%	93,67%
Inversor 2 C.T. 4	%	91,90%	92,66%	94,50%	94,20%	93,91%	94,13%	94,23%	94,54%	93,62%	94,00%	93,95%	92,43%	93,67%
Inversor 1 C.T. 5	%	91,94%	92,70%	94,55%	94,24%	93,96%	94,17%	94,28%	94,58%	93,66%	94,04%	93,99%	92,47%	93,71%
Inversor 2 C.T. 5	%	91,94%	92,70%	94,55%	94,24%	93,96%	94,17%	94,28%	94,58%	93,66%	94,04%	93,99%	92,47%	93,71%
Transformers performances														
Transformer C.T. 1	%	98,77%	98,81%	98,93%	98,91%	98,89%	98,91%	98,91%	98,94%	98,87%	98,90%	98,90%	98,80%	98,88%
Transformer C.T. 2	%	98,79%	98,83%	98,91%	98,90%	98,88%	98,89%	98,90%	98,91%	98,87%	98,89%	98,89%	98,82%	98,87%
Transformer C.T. 3	%	98,48%	98,53%	98,64%	98,62%	98,61%	98,62%	98,63%	98,64%	98,59%	98,61%	98,61%	98,51%	98,59%
Transformer C.T. 4	%	98,79%	98,83%	98,90%	98,89%	98,88%	98,89%	98,89%	98,91%	98,87%	98,88%	98,88%	98,82%	98,87%
Transformer C.T. 5	%	98,79%	98,83%	98,91%	98,89%	98,88%	98,89%	98,90%	98,91%	98,87%	98,89%	98,88%	98,82%	98,87%
Wiring performances														
Wiring DC	%	98,31%	98,31%	98,31%	98,31%	98,31%	98,31%	98,31%	98,31%	98,31%	98,31%	98,31%	98,31%	98,31%
Wiring between string and box	%	99,56%	99,56%	99,56%	99,56%	99,56%	99,56%	99,56%	99,56%	99,56%	99,56%	99,56%	99,56%	99,56%
Wiring between box and inverter	%	98,74%	98,74%	98,74%	98,74%	98,74%	98,74%	98,74%	98,74%	98,74%	98,74%	98,74%	98,74%	98,74%
Wiring AC	%	99,79%	99,79%	99,79%	99,79%	99,79%	99,79%	99,79%	99,79%	99,79%	99,79%	99,79%	99,79%	99,79%
Wiring between inverter and C.T.	%	99,80%	99,80%	99,80%	99,80%	99,80%	99,80%	99,80%	99,80%	99,80%	99,80%	99,80%	99,80%	99,80%
Wiring between C,T, and meter	%	99,99%	99,99%	99,99%	99,99%	99,99%	99,99%	99,99%	99,99%	99,99%	99,99%	99,99%	99,99%	99,99%

To understand better this data, below there are two graphs (fig. 3.3.3.1 and 3.3.3.2), as it has been done before with the partial loads, to see the difference that exists between these efficiencies and the theoretical maximum efficiency.

It is very important to note that these values are theoretical and not real.

It has been taken the same items as an example of the rest, to perform the analysis: inverter 1 of the C.T.1 and the transformer 1.

As shown in the graphs in figures 3.3.3.1 and 3.3.3.2, the inverters are those giving a lower efficiency compared to the optimum one, while the transformer gives a performance very close to the ideal one.

In the previous section, it has been observed that the transformer doesn't work even close to the optimal load for the maximum efficiency but it still gives a performance very tight to the optimal. This indicates that the efficiency of the transformer is not influenced greatly by their working load.

However, the efficiency of inverters is influenced by its working load and its efficiency decreases because its working load is distant to the optimal. This efficiency could be improved, realizing a better design of the inverters, adjusting the load to the optimum load. In short, for a better efficiency of the global PV plant, it would be necessary to have overloaded even more the inverters in the design phase.

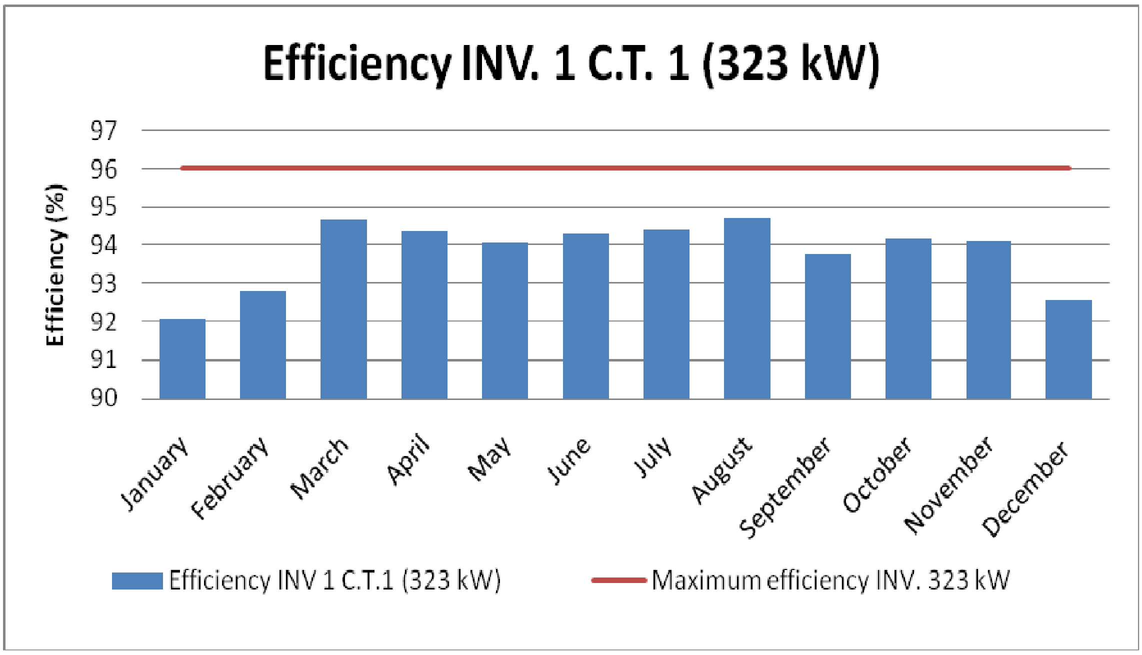


Figure 3.3.3.1-. Efficiency of the inverter 1 of C.T.1

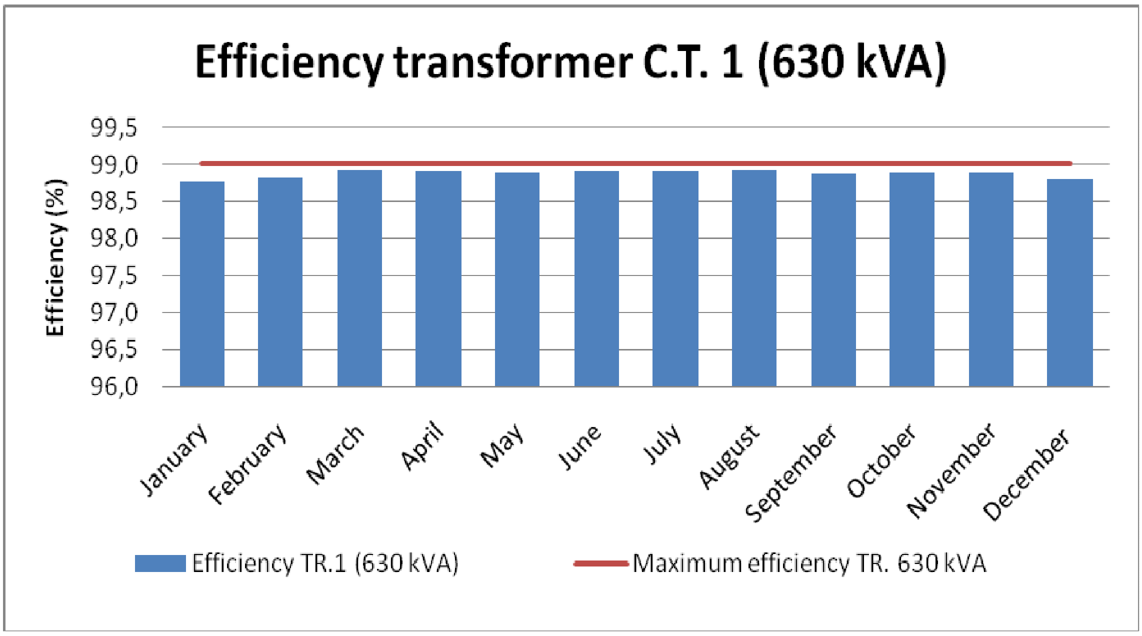
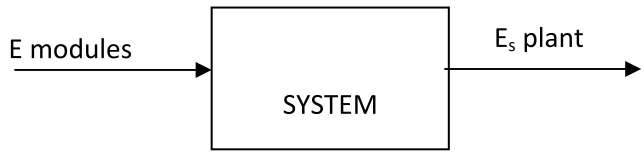


Figure 3.3.3.2-. Efficiency of the transformer of C.T.1

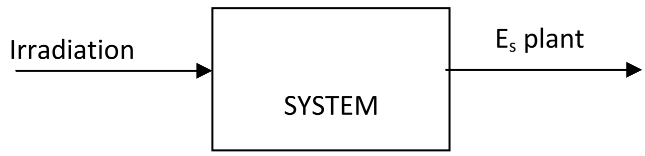
3.3.4 Performance ratio (PR) and global performance of the PV plant calculation.

With all these performances of the inverters, the transformers and the wiring it can be obtained the Performance Ratio (PR) and the global performance of the PV plant.

- **"Performance Ratio (PR)":** Indicates the percentage of electricity that is exported to the grid compared to the energy absorbed by the photovoltaic modules.



- **Global performance of the PV plant:** Indicates the percentage of electricity exported to the grid compared to the overall irradiation that arrives to the PV modules.



First, it has been performed the global performance of the part of the plant that uses DC, which includes the performance of photovoltaic modules, the losses due to temperature and dirtiness in the modules and the losses in the DC wiring. Then, it has been calculated the performance of the part of the plant that uses AC, which includes the performance of inverters, transformers and AC wiring. Finally, it can be obtained the overall performance of the plant as the product of these two performances that embraces the entire photovoltaic plant.

The performance ratio (PR) calculated below (table 3.3.4.1), is merely the performance of the installation regardless of the performance of photovoltaic modules. It is calculated as a performance of the plant with the electrical energy generated in the PV modules as the input energy.

Table 3.3.4.1-. The calculated performance ratio (PR)

P.V. Abrera 2010														
	Units	January	February	March	April	May	June	July	August	September	October	November	December	Total
Global efficiencies														
DC global efficiency	%	13,07%	13,07%	12,93%	12,90%	12,70%	12,41%	12,27%	12,14%	12,54%	12,66%	12,86%	13,07%	12,72%
AC global efficiency	%	90,14%	90,98%	93,01%	92,67%	92,36%	92,60%	92,72%	93,05%	92,03%	92,45%	92,40%	90,72%	92,09%
Global theoretical PV plant efficiency	%	11,79%	11,90%	12,03%	11,95%	11,73%	11,49%	11,38%	11,29%	11,54%	11,71%	11,89%	11,86%	11,71%
Theoretical Performance Rate (PR)	%	84,18%	84,97%	85,91%	85,38%	83,80%	82,08%	81,29%	80,67%	82,42%	83,63%	84,90%	84,73%	83,68%

It is interesting to observe the influence that does the photovoltaic modules performance of 14% on the overall performance of the plant. This PV plant regardless of this performance, works in an average of 83,68% theoretically, a very consistent and high performance rate for a photovoltaic plant of these dimensions.

Below are shown two graphs (figures 3.3.4.1 and 3.3.4.2) very significant for the PV plant, they show the evolution of the radiation that reaches the PV plant and its performance for each month. As it can be seen, during the time of the year with higher irradiation, the efficiency of the photovoltaic plant is lower.

The temperature factor of the modules has a greater influence on the performance rate than the performance of the inverters. This factor decrease the modules performance, and so, the global performance of the plant, when the cells temperature exceeds 25 ºC, in summer. While the inverters cause a minor decrease in the global efficiency, because they directly depend on the workload supported, and its efficiency is affected every month in a similar percentage. As it has been explained before, this decrease of the efficiency due to the low workload of the inverters can be solved by increasing number of modules of each inverter to increase the workingload.

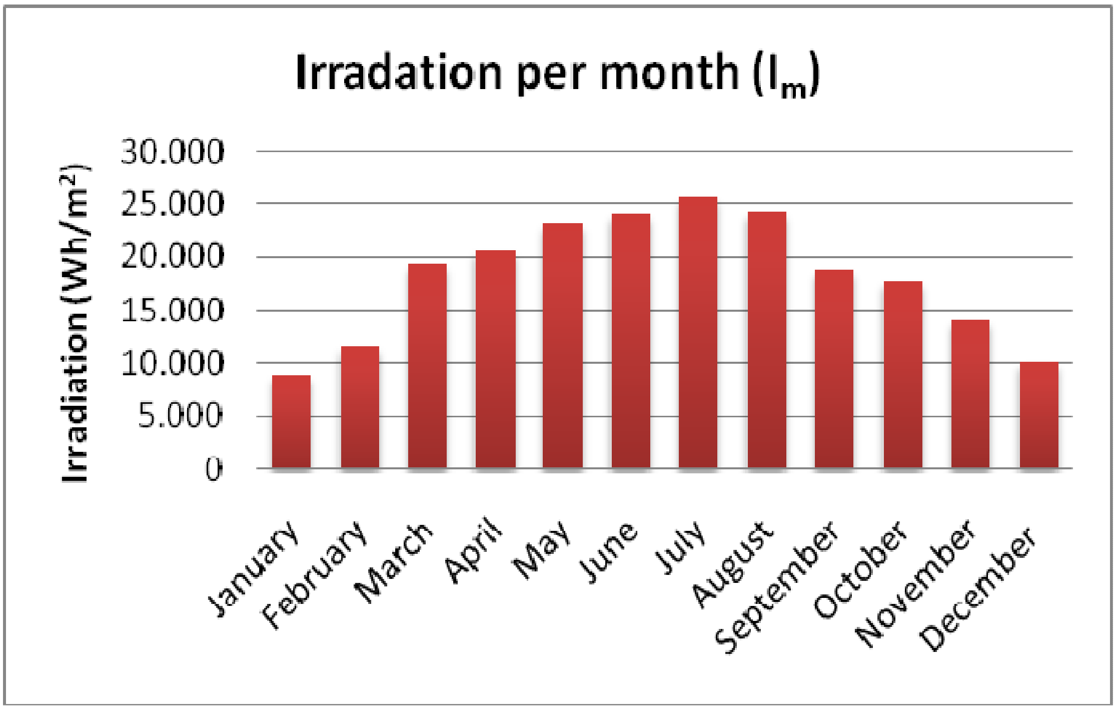


Figure 3.3.4.1-. Irradiation per month with 30º of inclination

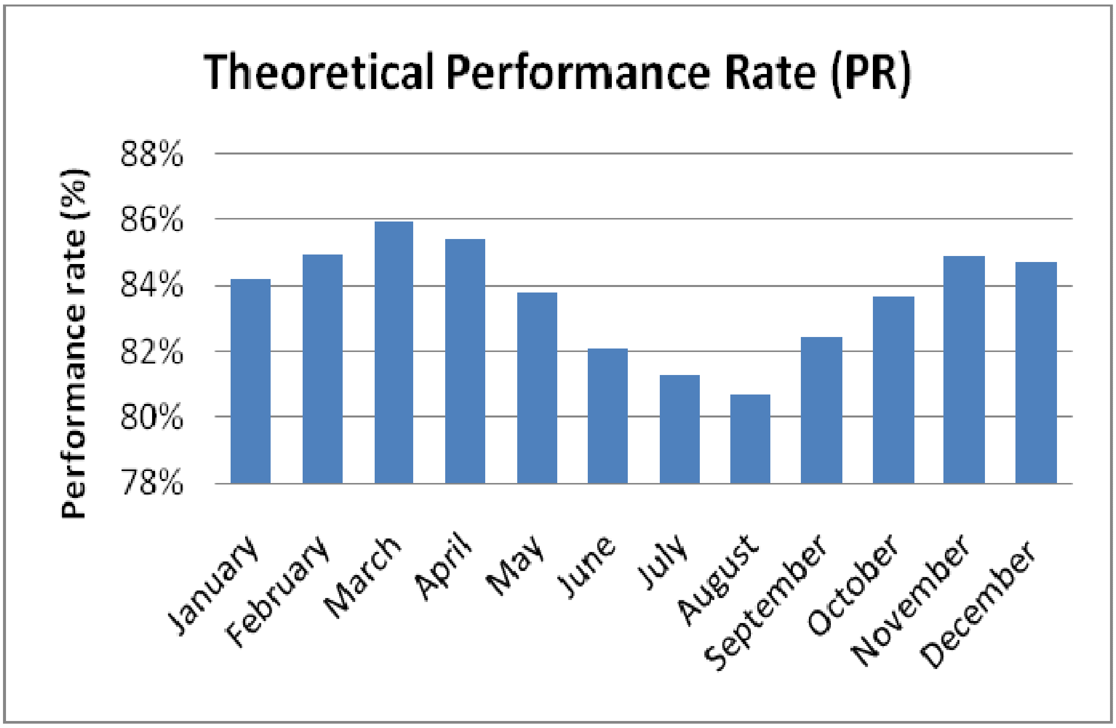


Figure 3.3.4.2-. Theoretical performance rate (PR) calculated

3.3.5 Calculation of electricity generation, CO_2 emissions and remuneration.

Once analyzed the theoretical performance of photovoltaic plant, it has proceeded to calculate the theoretical electrical energy generated in the phtovoltaic plant object, the main object of this study, as follows:

$$E_{elec\,generated}\,(kWh) = \frac{P_N(kW) \cdot HSP(h) \cdot \eta_{plant}}{\eta_{modules}} = P_N(kW) \cdot HSP(h) \cdot PR$$

Where:

- $E_{elec\,generated}$ is the final electrical energy generated in the PV plant.
- $P_N\,(kW)$ is the nominal power of the PV plant.
- HSP are the equivalent peak hours received by the photovoltaic plant monthly.
- η_{plant} is the theoretical performance of the overall plant.
- $\eta_{modules}$ is the performance of the photovoltaic modules, given by the manufacturer.
- PR is the performance rate calculated before.

For the calculation of CO_2 emissions avoided by using solar energy instead of conventional fossil fuels, it has been used the ratio of 411,5 $^{g_{CO_2}}/_{\text{kWh}_e}$ generated, so:

$$e_{CO_2}(\text{tones CO}_2) = \frac{\left(E_{elec\,generated}\,(kWh) - E_{elec\,bought}\,(kWh)\right) * 411{,}5\ ^{g_{CO_2}}/_{kWh_e}}{10^6\ ^{g_{CO_2}}/_{tones\ CO_2}}$$

Where:

- e_{CO_2} are the CO_2 emissions avoided.
- $E_{elec\,generated}$ is the final electrical energy generated by the PV plant calculated before.
- $E_{elec\,bought}$ is the electricity bought to the electrical company that feeds the equipment that consumes energy: inverters, illumination, ventilation and control system. These data have been collected from the real bills of the PV plants.

As for the theoretical remuneration calculated, taken into account the price set by the ITC 3519-2009 where is stipulated the rate of 44,169 $^{c€}/_{kWh}$ for the whole 2010. This income will always be proportional to the energy generated by the photovoltaic plant.

The following table (table 3.3.5.1) summarizes the electricity generation, CO_2 emissions avoided and the remuneration (excluding VAT) for every month of 2010:

Table 3.3.5.1-. Theoretical electricity generation, avoided CO_2 emissions and the remuneration (excluding VAT) for every month of 2010

P.V. Abrera 2010														
	Units	January	February	March	April	May	June	July	August	September	October	November	December	Total
Theoretical electricity generated *(Eelec generated)*	kWh	155.101,67	204.937,21	346.455,07	365.591,72	405.099,84	411.308,70	435.336,76	407.490,84	320.895,07	309.570,18	246.908,05	178.354,00	3.787.049
Theoretica CO2 emissions *(eCO2)*	tones CO2	62,55	83,28	141,45	149,56	165,85	168,49	178,34	166,83	131,13	126,34	100,45	72,10	1.546
Theoretical remuneration for the sale of electricity	€	67.134,08	89.385,78	151.822,58	160.529,02	178.018,67	180.852,49	191.425,25	179.073,87	140.755,15	135.611,28	107.816,99	77.392,92	1.659.818

Theoretically, this PV plant has helped the country to save 1546 tones of CO_2 in the year 2010. This is one of the advantages of using this technology, which respects the environment, the same way that take advantage of the resources that nature offers. At the same time, if it is compared the performance rate with the electrical energy generated, it can be observed that the greatest generation is given those months that has lower performance rate. The results of the calculations are presented in the figures 3.3.5.1 and 3.3.5.2.

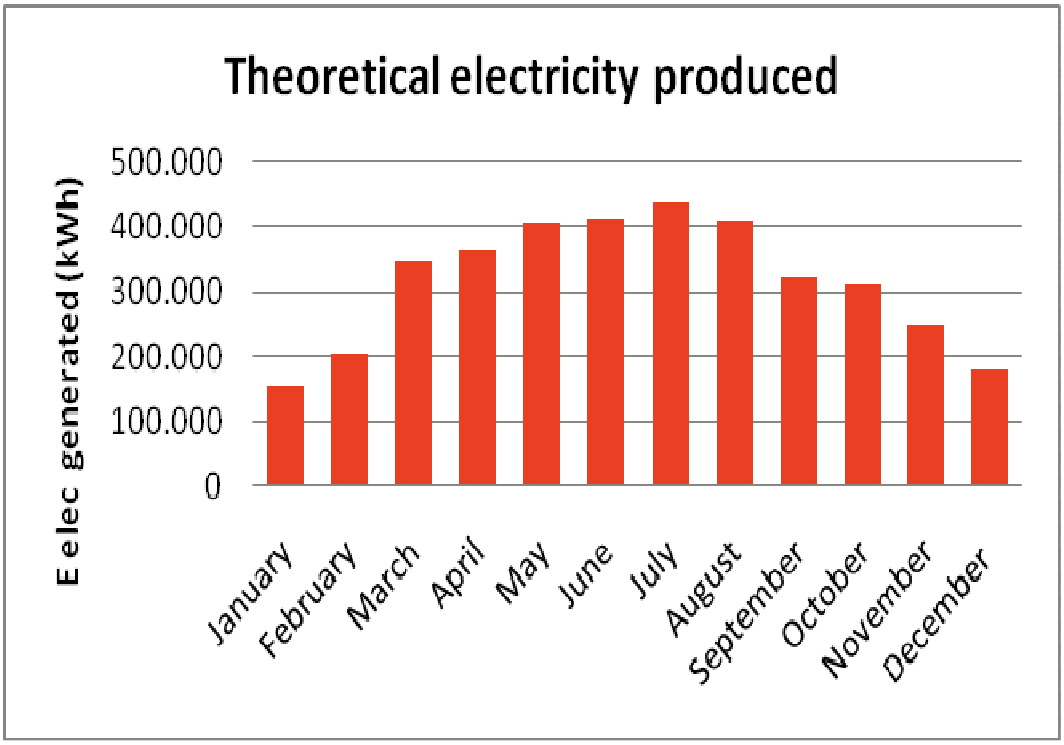


Figure 3.3.5.1-. Theoretical electricity production for 2010

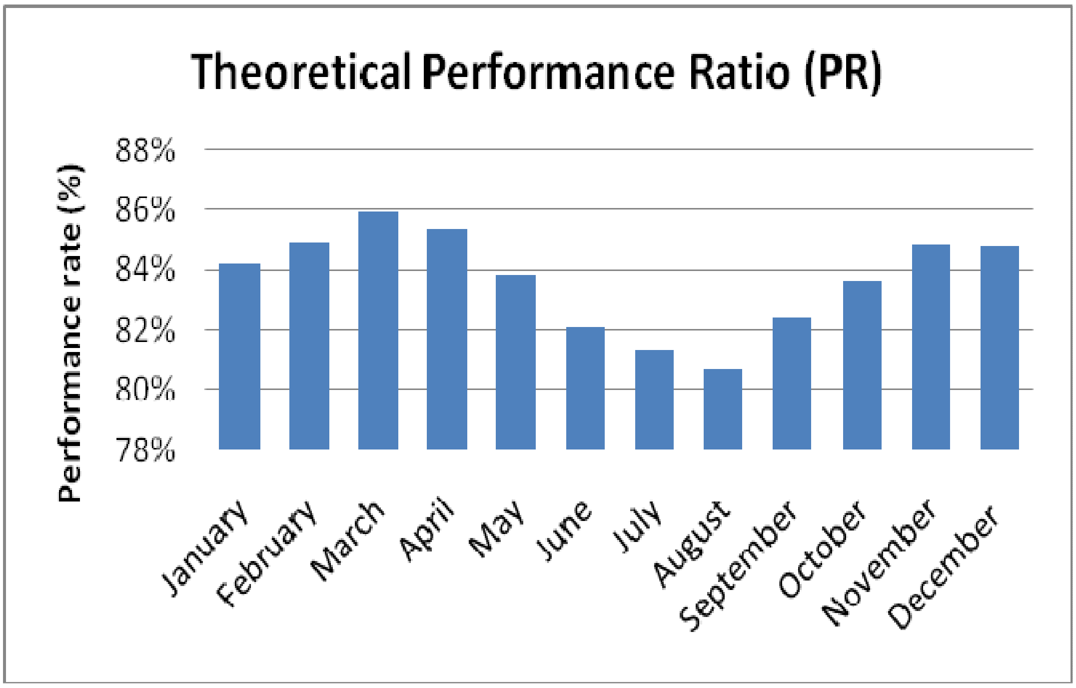


Figure 3.3.5.2-. Theoretical performance ratio (PR) calculated for 2010

3.4 REAL VALUES GIVEN BY THE PV PLANT

To verify the theoretical values calculated, is has been necessary that the staff responsible for the photovoltaic plant in Abrera, provide the real values obtained directly from the facilities.

These data are:

- The average daily radiation incident on the modules tilted 30º on the horizontal, measured with radiation probes in the facilities. It should be noted that during the months of January and December, the probes did not work properly, thus the data considered were from the meteorological station situated in Els Hostalets de Pierola, the nearest to the PV plant. This average daily irradiation has been the base data for the theoretical calculations previously analysed.

- The electricity bought and sold, based on readings of the meter property of the electrical company ENDESA DISTRIBUCION ELECTRICA S.A. The sold electricity is the final electricity generated in the PV plant, which will be compared to the final theoretical electricity generated calculated before. The bought energy, the one that feed the equipment that consumes energy, will be necessary to calculate the CO_2 emissions avoided, as it can be seen in the previous section.

- Technical description of the equipment of the PV plant, together with the description of the scheme of the photovoltaic plant and the geographical location.

With the electrical energy sold, or what is the same, the electrical energy generated, it is possible to calculate the real performance rate, to be able afterwards to compare it to the one calculated theoretically before.

Thus, the calculation is:

$$PR_{real} = \frac{E_{real\,gen}}{P_N \cdot HSP(h)}$$

Where:

- PR_{real} is the real performance rate of the photovoltaic plant.
- $E_{real\,gen}$ is the real electrical energy generated by the PV plant given by the staff of the photovoltaic plant.
- $P_N\,(kW)$ is the nominal power of the PV plant calculated from the nominal powers of the different elements of the plant.
- $HSP(h)$ equivalent peak hours received by the photovoltaic plant monthly.

For later comparison of the theoretical and the real values, it has been calculated the real CO_2 emissions avoided and the real remuneration for the sale of electricity to the electrical company, with the same method used theoretically.

Below (table 3.4.1) there are presented the real values provided by the staff responsible for the photovoltaic plant and the real values calculated from them: real performance rate, real CO_2 emissions avoided and the real remuneration obtained from the sale of electricity produced.

Table 3.4.1-. Real values for electricity generation, performance rate (PR)**,** CO_2 avoided emissions and remuneration for 2010.

P.V. Abrera 2010														
	Units	January	February	March	April	May	June	July	August	September	October	November	December	Total
Irradation with inclination (30º) *(Im)*	Wh/m2	66.121,41	86.557,26	144.729,78	153.664,51	173.481,80	179.822,86	192.192,86	181.275,46	139.719,37	132.833,10	104.367,37	75.543,25	1.630.309
Real electricity generated *(E real gen)*	kWh	149.130,00	200.578,00	324.760,00	347.803,00	387.830,00	397.784,00	418.318,00	400.248,00	321.323,00	296.086,00	238.844,00	171.504,00	3.654.208
Real electrigity bought *(E elec bought)*	kWh	3.108	2.565	2.724	2.149	2.060	1.853	1.944	2.062	2.221	2.542	2.807	3.134	29.169
Real performance rate *(PR real)*	%	80,94%	83,16%	80,53%	81,23%	80,23%	79,38%	78,11%	79,24%	82,53%	79,99%	82,13%	81,47%	80,44%
Real CO2 emissions *(eCO2 real)*	tones CO2	60,09	81,48	132,52	142,24	158,74	162,93	171,34	163,85	131,31	120,79	97,13	69,28	1.491,70
Real remuneration for the sale of electricity	€	64.873	88.011	144.906	154.074	171.823	176.290	184.518	177.352	142.320	131.121	104.937	76.176	1.616.401

In the folowing graphs (figure 3.4.1 and 3.4.2) it can be seen the evolution of the solar irradiation, the real electricity generated and the real performance rate calculated.

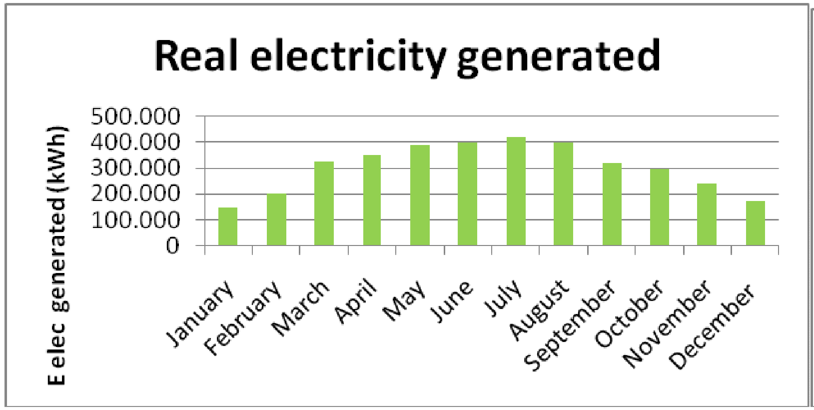


Figure 3.4.1-. Real electricity production for 2010

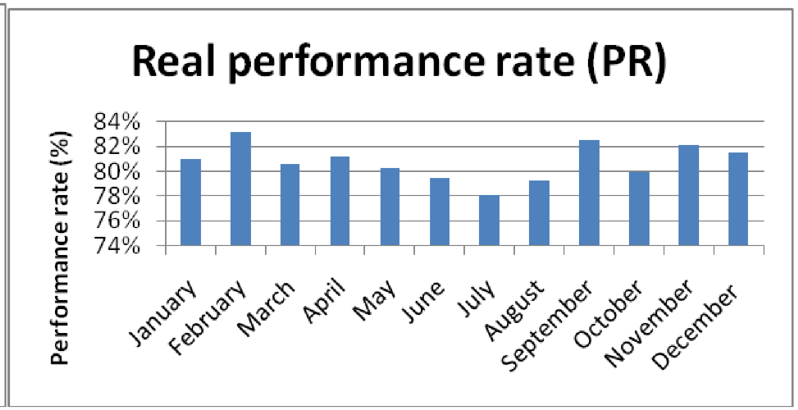


Figure 3.4.2-. Real performance rate (PR) for 2010

As it can be seen from the presented plots, this generated real electricity follows the same tendency during the year as the theoretical one, i.e. calculated one, while the performance rate doesn’t follow exactly the same trend line. In the next section, these values are compared with the theoretical values calculated and the results are analysed.

3.5 COMPARISON BETWEEN THE THEORETICAL AND THE REAL VALUES.

Once completed all the calculations, I will proceed to compare the theoretical values obtained with the real values given by the staff responsible of the PV plant, to analyze the reliability and availability of the facility, calculated as the real energy generated divided by the theoretical energy generated.

In figure 3.5.1, it is shown graphically the comparison between the theoretical electricity generated exported, the real energy generated and exported and the reliability and availability percentage.

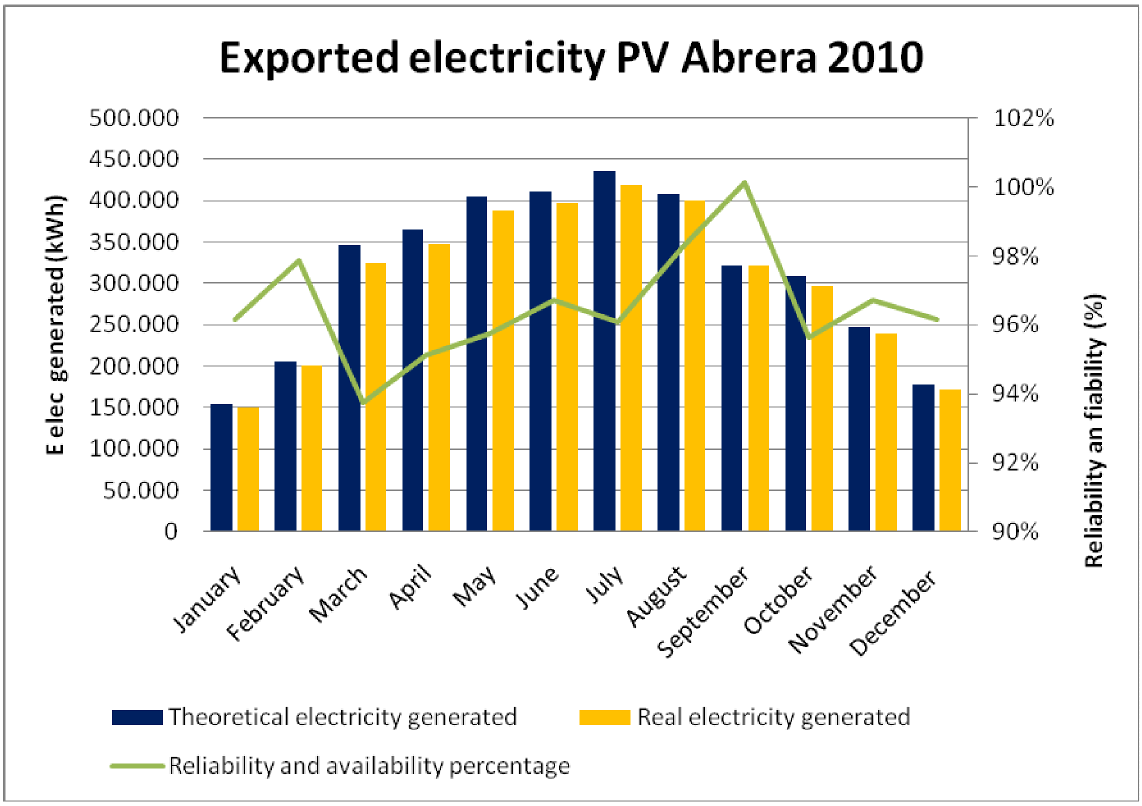


Figure 3.5.1-. Comparison of the values obtained in this project with real ones

From the fig. 3.5.1, it can be seen that there is decrease in the reliability and availability percentage of the plant in the months of March and October, which has let to stop generating 132.841,12 kWh representing a 3,64% of the real electricity generated in the PV plant. This indicates that the reliability of the photovoltaic plant is very high, since the theoretical calculations are in accordance with the real values of electricity generated. It can be also seen that the prposed method of the modeling used in this project is proper and very close to the values obtained during the real plant in 2010.

In terms of CO_2 emissions avoided (fig. 3.5.2), the difference between real and theoretical values is proportional to the difference between the theoretical and real values of electricity generation, so hence it can be also concluded that using the proposed theoretical method ona can also evaluate the impact on environment according to the ecological standards. As can be observed in this graph, the difference between real and theoretical CO_2 emissions avoided by using the PV power plant is really low, having calculated 1 546,36 CO_2 tones avoided, and being really at the level of 1 491,7 CO_2 tones.The difference is about 54, 66 CO2 tones which is not very high within the range of values (relatively about 3%).

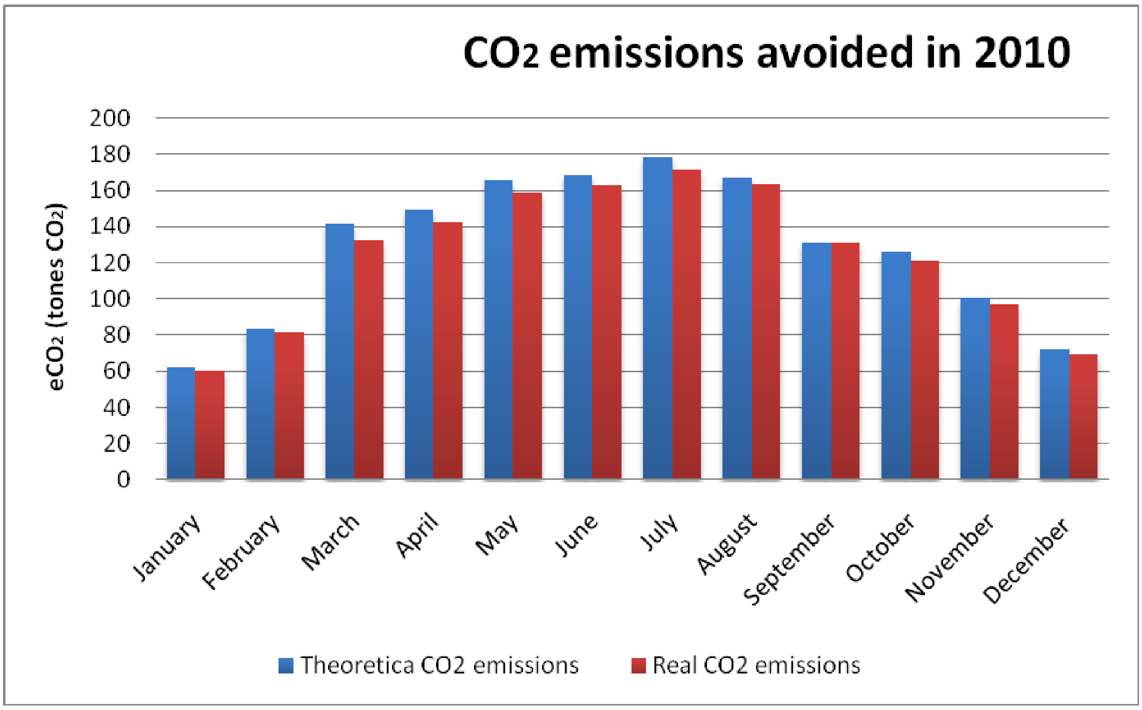


Figure 3.5.2-. Ecological impact according to the project and the reality

From the remuneration from the sale of electricity (figure 3.5.3) it could be obtained the similar result. The difference is proportional to the difference between theoretical and real electricity generation, and hence it can be modelled basing of the obtained data.

Looking at the problem from the economical point of view, the annual difference existing between the calculated theoretical and the real income is 43 417,20 €, which means about 2,69% of the real income for the sale of electricity. The theoretical electricity production of the photovoltaic plant is higher that the real one, so it causes a decrease in the income. This leads to an increase in payback of the initial investment of the photovoltaic plant, but it will have little significance. If we consider that the payback of a photovoltaic plant is about 12 years, this decrease in the income suppose approximately 4 months more to recover the initial investment.

Finally, it will be compared the performance rate of the photovoltaic plant, or what is the same, the performance of the installation, theoretical calculated with the real one (fig. 3.5.3), the aim of this study.

Although, the performance rate evolution is hardly appreciated, as it has been shown before, it can be observed that during the warmest months, in summer, the performance rate is always lower that the annual average, while the rest of the year is over it. This is caused by the influence of the temperature cell in the solar photovoltaic plant performance.

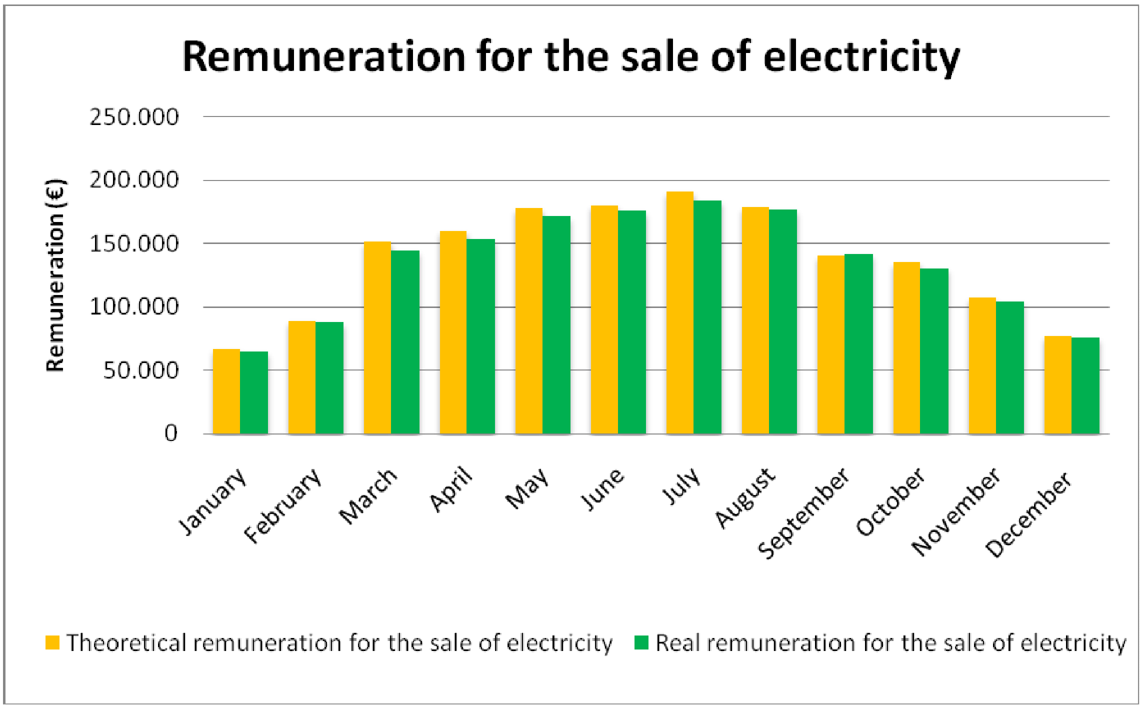


Figure 3.5.3-. Remuneration for the sale of electricity according to the project and the real values

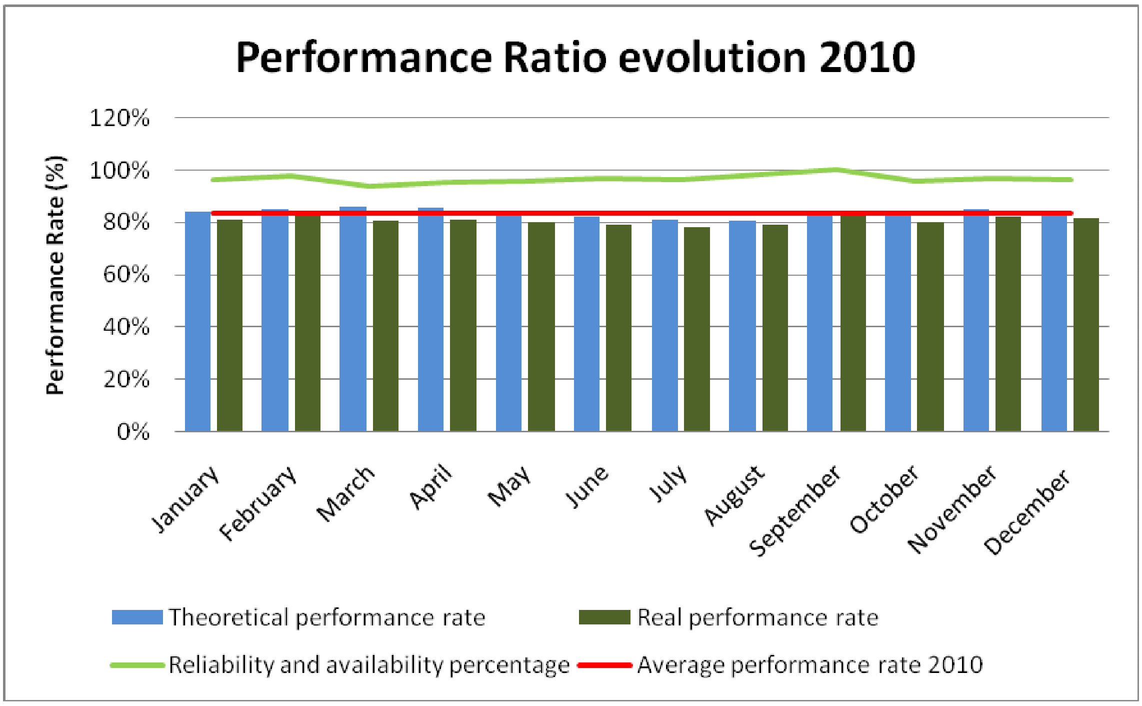


Figure 3.5.4-. Performance rate of the photovoltaic plant according to the project and the real values

In addition, it can be observed the decrease in reliability in the months of March and October that shows that there are months where there have been big differences between the real and calculated performance rates. This could be due to maintenance actions carried out in those months in the photovoltaic plant in Abrera, confirmed by the staff of the photovoltaic plant. This difference exists because the maintenance actions are not covered by the theoretical calculations.

4. CONCLUSIONS

Having carried out the study of the photovoltaic plant can be drawn different conclusions regarding the design and its operating characteristics.

Initially, one might think that a photovoltaic plant performance would be higher during the period when the modules receive greater irradiation. This project proves that this idea is a misconception and, in contrast, the performance is lower in the months of greatest solar radiation. This occurs because the overall performance of the plant is largely influenced by the temperature of the photovoltaic cells. These cells decrease their performance when their temperature exceeds 25 ºC, so in summer, when they reach a temperature of 41 ºC, the performance is significantly reduced.

In addition, the overall performance of the photovoltaic plant is also influenced by the inverters of the plant. It can be observed during the study, that the performance of these inverters directly depends on the workload supported. In this case, real inverters are working below the optimal partial loads for maximum performance, which makes the overall performance of the plant decreases considerably.

By contrast, when studying the case of transformer it has been verified that its performance does not depend hardly on its partial loads, what means that even though the partial loads of the transformers are less than the optimal loads for working under a maximum efficiency, they do not influence significantly on the overall performance of the photovoltaic plant studied.

Thus, the performance of the plant is influenced by the average temperature of the photovoltaic cells and the inverters performance, though, after the shown analyze, I can ensure that the temperature factor has a more important weight.

To increase the overall performance, inverters should be overloaded in the design stage, later their partial loads meet the optimal values to improve the performance.

Generally speaking, during the first years of energy production in case of a photovoltaic plant, the generated energy will fit the expected one, just because the facilities will have not suffered degradation yet. The analysed plant was implemented in 2008, thus, according to the reliability calculated for 2010, it can be seen that the production of the plant fits the operational values described theoretically.

As it has been observed, the reliability of the plant has been reduced during March and October, the months in which maintenance actions are performed on the facilities.

Last but not least, it is important to remember that the solar photovoltaic energy is a clean and beneficial energy for humanity. As it has been verified, the emissions avoided by using this technology instead of fossil fuels, has been of 1 491,7 tones of CO_2 just in 2010. In addition, it has remuneration for the sale of the electricity generated that let recover the initial investment with a reasonable period of time, with the legislation applied to this photovoltaic plant.

As it has been seen in this project, solar photovoltaic energy is a present situation for Spain. To get to this point, the government has had to make an effort to pay subsidies to promote the implementation of photovoltaic plants. This has caused a huge deficit fare in Spain that together with having reached the quota of photovoltaic power energy installed predicted for 2015, are currently causing the withdrawal of these grants, and therefore becoming a technology of present and not of future.

Finally, after having acquired knowledge on the subject, it can be observed that the implementation of photovoltaic plants in Poland is not viable due to the low radiation received annually, compared to Spain. It must be mentioned that the temperatures are not as high as in Spain, so, in consequence, the overall performance rate of the photovoltaic would be higher than in Spain, being well sized. Anyway, with the low electricity production, due to the low annual radiation, the income would be poor, and the payback would be too high to be viable a photovoltaic plant in Poland.

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